Global analysis of $b \to s\ell\ell$ anomalies: Better driving the ambulance than chasing it*

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Based on: DMV'13 **PRD88 (2013) 074002**, DHMV'14 **JHEP 1412 (2014) 125**, JM'12 **PRD86 (2012) 094024** HM'15 **JHEP 1509(2015)104**, DHMV'15 **1510.04239 (updated with final data)** and CDHMV'16 (to appear)

All originated in Frank Krueger, J.M., Phys. Rev. D71 (2005) 094009

*** Recommended for bump chasers: arXiv: 1603.01204**

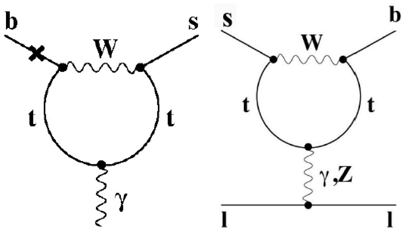
Goal of this talk

This talk is divided in three parts:

- What does the global fit on $b \to s\ell\ell$ tell us about Wilson coefficients?
  - Description of anomalies and tensions in semileptonic B decays.
  - Which Wilson coefficients/scenarios receive a dominant NP contribution?
- Anatomy of hadronic uncertainties.
  - Theoretical description of $B \to K^*\mu\mu$ at low-q^2 in a nutshell.
  - Deconstructing attempts to try to explain **only some anomaly** showing where those arguments fail.
- Possible NP explanations and a glimpse into the future.

Analysis of FCNC in a model-independent approach, effective Hamiltonian:

$$b \to s\gamma(^*) : \mathcal{H}_{\Delta F=1}^{SM} \propto \sum_{i=1}^{10} V_{ts}^* V_{tb} \mathcal{C}_i \mathcal{O}_i + \ldots$$



- $\mathcal{O}_7 = \frac{e}{16\pi^2} m_b (\bar{s}\sigma^{\mu\nu} P_R b) F_{\mu\nu}$
- $\mathcal{O}_9 = \frac{e^2}{16\pi^2} (\bar{s}\gamma_\mu P_L b)\ (\bar{\ell}\gamma_\mu \ell)$
- $\mathcal{O}_{10} = \frac{e^2}{16\pi^2} (\bar{s}\gamma_\mu P_L b)\ (\bar{\ell}\gamma_\mu \gamma_5 \ell)$, ...

• **SM** Wilson coefficients up to NNLO + e.m. corrections at $\mu_{ref} = 4.8$ GeV [Misiak et al.]:

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

• **NP** changes short distance $\mathcal{C}_i - \mathcal{C}_i^{\rm SM} = \mathcal{C}_i^{\rm NP}$ and induces new operators: $\mathcal{O}'_{7,9,10} = \mathcal{O}_{7,9,10}\ (P_L \leftrightarrow P_R)$ ...

also scalars, pseudoescalar, tensor operators...

The way to obtain information on those Wilson coefficients is via a GLOBAL FIT to the relevant processes.

DHMV'15 1510.04239 (updated with final LHCb data 1512.04442)

Updated GLOBAL FIT 2016:

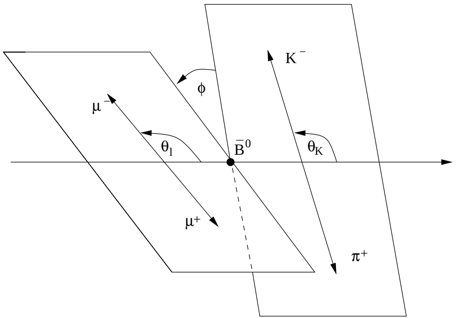
THE OBSERVABLES

- Inclusive
  - $B \to X_s\gamma$ (BR) .... $\mathcal{C}_7^{(\prime)}$
  - $B \to X_s\ell^+\ell^-$ (dBR/dq^2) .... $\mathcal{C}_7^{(\prime)}, \mathcal{C}_9^{(\prime)}, \mathcal{C}_{10}^{(\prime)}$
- Exclusive leptonic
  - $B_s \to \ell^+\ell^-$ (BR) .... $\mathcal{C}_{10}^{(\prime)}$
- Exclusive radiative/semileptonic
  - $B \to K^*\gamma$ (BR, S, A_I) .... $\mathcal{C}_7^{(\prime)}$
  - $B \to K\ell^+\ell^-$ (dBR/dq^2) .... $\mathcal{C}_7^{(\prime)}, \mathcal{C}_9^{(\prime)}, \mathcal{C}_{10}^{(\prime)}$
  - $\mathbf{B} \to \mathbf{K}^*\ell^+\ell^-$ (dBR/dq^2, **Optimized Angular Obs.**) .. $\mathcal{C}_7^{(\prime)}, \mathcal{C}_9^{(\prime)}, \mathcal{C}_{10}^{(\prime)}$
  - $B_s \to \phi\ell^+\ell^-$ (dBR/dq^2, Angular Observables) .... $\mathcal{C}_7^{(\prime)}, \mathcal{C}_9^{(\prime)}, \mathcal{C}_{10}^{(\prime)}$
  - $\Lambda_b \to \Lambda\ell^+\ell^-$ (None so far)
  - etc.

Optimized Basis of Angular Observables for $B \to K^*\mu\mu$

The **optimized observables** $P_i^{(\prime)}$ come from the angular distribution $\mathbf{\bar{B}_d} \to \mathbf{\bar{K}^{*0}}(\to \mathbf{K}^-\pi^+)\mathbf{l^+l^-}$ with the K^{*0} on the mass shell. It is described by $\mathbf{s} = \mathbf{q^2}$ and three angles θ_ℓ, $\theta_{\mathbf{K}}$ and ϕ

$$\frac{d^4\Gamma(\bar{B}_d)}{dq^2\, d\cos\theta_\ell\, d\cos\theta_K\, d\phi} = \frac{9}{32\pi}\mathbf{J}(\mathbf{q^2}, \theta_\ell, \theta_K, \phi) = \sum_i J_i(q^2) f_i(\theta_\ell, \theta_K, \phi)$$



Non-optimal obs.: $S_i = (J_i + \bar{J}_i)/(d\Gamma + d\bar{\Gamma})$

θ_ℓ: Angle of emission between $\bar{K}^{*0}$ and μ^- in di-lepton rest frame.
$\theta_{\mathbf{K}}$: Angle of emission between $\bar{K}^{*0}$ and K^- in di-meson rest frame.
ϕ: Angle between the two planes.

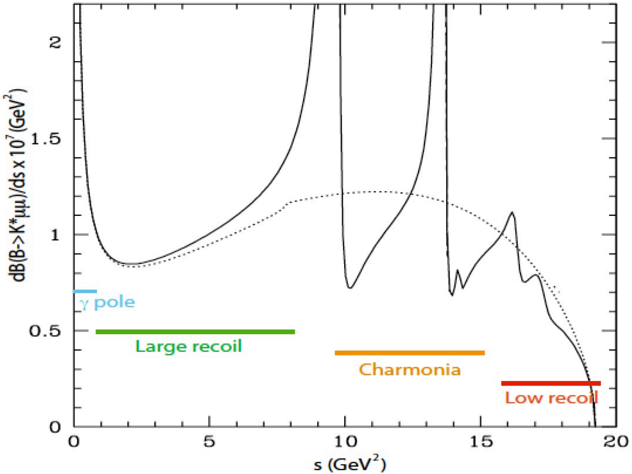
$\mathbf{q^2}$: dilepton invariant mass square.

$$\frac{1}{\Gamma'_{full}}\frac{d^4\Gamma}{dq^2\, d\cos\theta_K\, d\cos\theta_l\, d\phi} = \frac{9}{32\pi}\Bigg[\frac{3}{4}\mathbf{F_T}\sin^2\theta_K + \mathbf{F_L}\cos^2\theta_K + (\frac{1}{4}\mathbf{F_T}\sin^2\theta_K - \mathbf{F_L}\cos^2\theta_K)\cos 2\theta_l$$

$$+\sqrt{\mathbf{F_T F_L}}\left(\frac{1}{2}\mathbf{P'_4}\sin 2\theta_K \sin 2\theta_l \cos\phi + \mathbf{P'_5}\sin 2\theta_K \sin\theta_l \cos\phi\right) + 2\mathbf{P_2 F_T}\sin^2\theta_K \cos\theta_l + \frac{1}{2}\mathbf{P_1 F_T}\sin^2\theta_K \sin^2\theta_l \cos 2\phi$$

$$-\sqrt{\mathbf{F_T F_L}}\left(\mathbf{P'_6}\sin 2\theta_K \sin\theta_l \sin\phi - \frac{1}{2}\mathbf{P'_8}\sin 2\theta_K \sin 2\theta_l \sin\phi\right) - \mathbf{P_3 F_T}\sin^2\theta_K \sin^2\theta_l \sin 2\phi\Bigg](1 - \mathbf{F_S}) + \frac{1}{\Gamma'_{full}}\mathbf{W_S}$$

Four regions in q^2



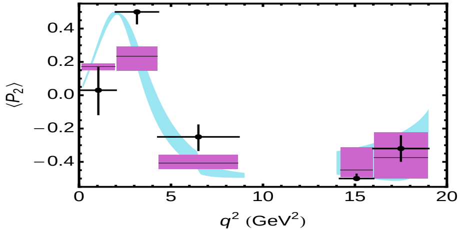
Four regions in q^2:

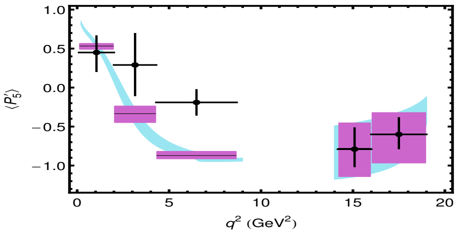
- **very large** K^*-recoil ($4m_\ell^2 < q^2 < 1$ GeV^2): γ almost real.
- **large** K^***-recoil/low-q**^{2}: $E_{K^*} \gg \Lambda_{QCD}$ or $4m_\ell^2 \leq q^2 < 9$ GeV^2: LCSR-FF
- charmonium region ($q^2 = m^2_{J/\Psi}, ...$) betwen $9 < q^2 < 14$ GeV^2.
- **low** K^***-recoil/large-q**^{2}: $E_{K^*} \sim \Lambda_{QCD}$ or $14 < q^2 \leq (m_B - m_{K^*})^2$: LQCD-FF

Brief flash on the anomalies

Why so much excitement in Flavour Physics? What changed in and after 2013?

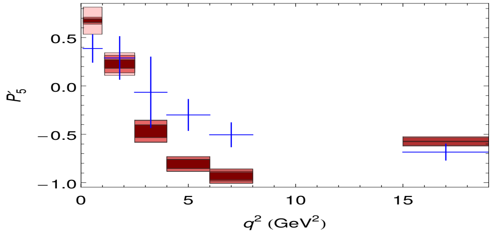
- First measurement by LHCb of the basis of optimized observables with 1 fb^{-1}:



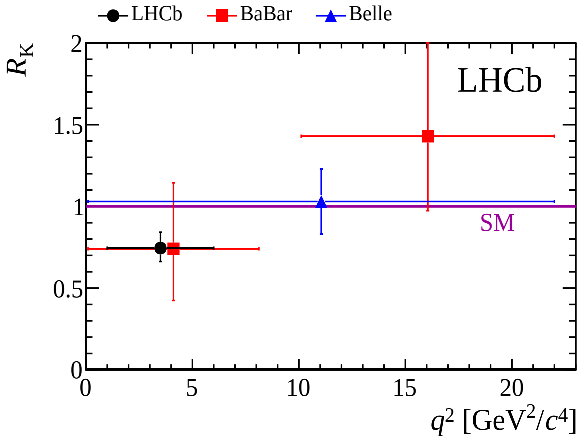


$\Rightarrow$ P_2 exhibited a **2.9**σ deviation in the bin [2,4.3] and P_5' exhibits a **3.7**σ in the [4.3,8.7] bin.

- In 2015 the so called anomaly in P_5' is confirmed with 3fb^{-1} in **2 bins** with **2.9**σ each:



$\Rightarrow$ P_2 will require a bit of patience (... a bit more data)



$$R_K = \frac{\mathrm{Br}\,(B^+ \to K^+\mu^+\mu^-)}{\mathrm{Br}\,(B^+ \to K^+e^+e^-)} = 0.745^{+0.090}_{-0.074} \pm 0.036$$

- It deviates **2.6**σ from SM.
- Data on $BR(B^+ \to K^+\mu^+\mu^-)$ is below SM

in **all bins** at large and low-recoil.

Also BR of neutral mode:

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

$10^7 \times BR(B^0 \to K^{*0}\mu^+\mu^-)$	Standard Model	Experiment	Pull
$[0.1, 2]$	1.30 ± 1.00	1.14 ± 0.18	$+0.2$
$[2, 4.3]$	0.85 ± 0.59	0.69 ± 0.12	$+0.3$
$[4.3, 8.68]$	2.62 ± 4.92	2.15 ± 0.31	$+0.1$
$[16, 19]$	1.66 ± 0.15	1.23 ± 0.20	$+\mathbf{1.7}$
$10^7 \times BR(B^+ \to K^{*+}\mu^+\mu^-)$	Standard Model	Experiment	Pull
$[0.1, 2]$	1.35 ± 1.05	1.12 ± 0.27	$+0.2$
$[2, 4]$	0.80 ± 0.55	1.12 ± 0.32	-0.5
$[4, 6]$	0.95 ± 0.70	0.50 ± 0.20	$+0.6$
$[6, 8]$	1.17 ± 0.92	0.66 ± 0.22	$+0.5$
$[15, 19]$	2.59 ± 0.24	1.60 ± 0.32	$+\mathbf{2.5}$
$10^7 \times BR(B_s \to \phi\mu^+\mu^-)$	Standard Model	Experiment	Pull
$[0.1, 2.]$	1.81 ± 0.36	1.11 ± 0.16	$+\mathbf{1.8}$
$[2., 5.]$	1.88 ± 0.32	0.77 ± 0.14	$+\mathbf{3.2}$
$[5., 8.]$	2.25 ± 0.41	0.96 ± 0.15	$+\mathbf{2.9}$
$[15, 18.8]$	2.20 ± 0.17	1.62 ± 0.20	$+\mathbf{2.2}$

Also $BR(B \to V\mu\mu)$ exhibit a systematic deficit with respect to SM, particularly $B_s \to \phi\mu\mu$.

Theory and experimental updates in 2016 fit

- $BR(B \to X_s\gamma)$
  - New theory update: $\mathcal{B}_{s\gamma}^{\rm SM} = (3.36 \pm 0.23) \cdot 10^{-4}$ (Misiak et al 2015)
  - $+6.4\%$ shift in central value w.r.t 2006 $\to$ excellent agreement with WA
- $BR(B_s \to \mu^+\mu^-)$
  - New theory update (Bobeth et al 2013), New LHCb+CMS average (2014)
- $BR(B \to X_s\mu^+\mu^-)$
  - New theory update (Huber et al 2015)
- $BR(B \to K\mu^+\mu^-)$:
  - LHCb 2014 + Lattice form factors at large q^2 (Bouchard et al 2013, 2015)
- $B_{(s)} \to (K^*, \phi)\mu^+\mu^-$: BRs & Angular Observables
  - LHCb 2015 + Lattice form factors at large q^2 (Horgan et al 2013)
- $BR(B \to Ke^+e^-)_{[1,6]}$ (or R_K) and $B \to K^*e^+e^-$ at very low q^2
  - LHCb 2014, 2015

Frequentist approach:

$$\chi^2(C_i) = [O_{\rm exp} - O_{\rm th}(C_i)]_j \, [Cov^{-1}]_{jk} \, [O_{\rm exp} - O_{\rm th}(C_i)]_k$$

- **Cov** $=$ **Cov**$^{\rm exp}$ $+$ **Cov**$^{\rm th}$. We have $Cov^{\rm exp}$ for the first time
- Calculate $Cov^{\rm th}$: correlated multigaussian scan over all nuisance parameters
- $Cov^{\rm th}$ depends on C_i: Must check this dependence

For the Fit:

- Minimise $\chi^2 \to \chi^2_{\rm min} = \chi^2(C_i^0)$ (Best Fit Point = C_i^0)
- Confidence level regions: $\chi^2(C_i) - \chi^2_{\rm min} < \Delta\chi_{\sigma,n}$

Definition of Pull$_{SM}$:

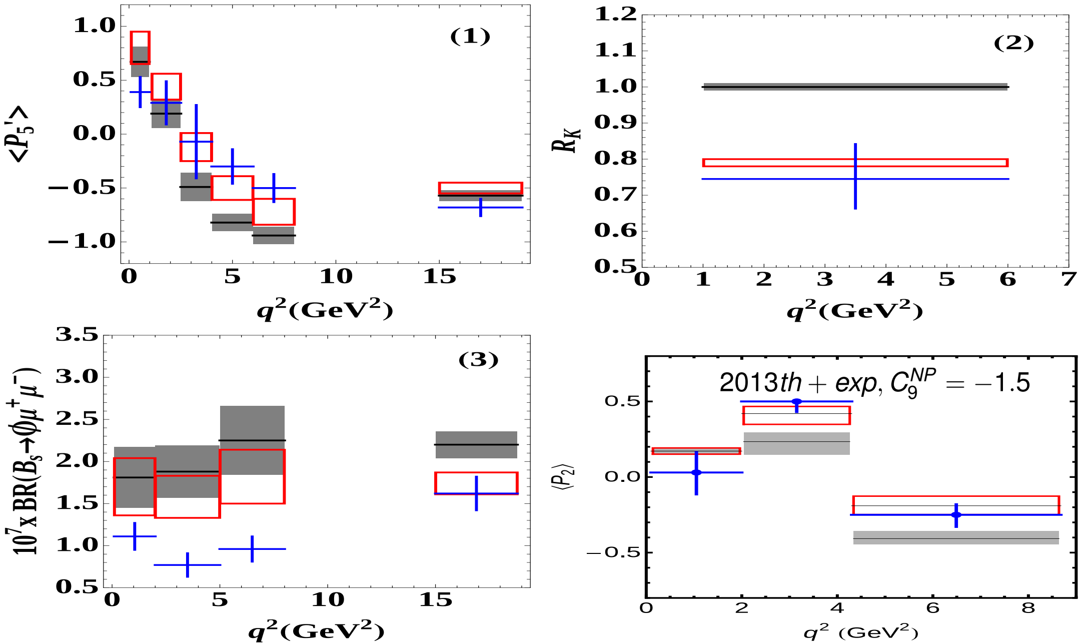
Pull$_{SM}$ tells you how much in a model defined by a set of free Wilson coefficients C_i the value preferred by data for these Wilson coefficients is in tension with C_i^{SM}.

Result of the fit with 1D Wilson coefficient 2016 (e^+e^- mode not included)

This is the first analysis: - using the basis of **optimized observables** ($B \to K^* \mu\mu$ and $B_s \to \phi\mu\mu$)
- using the **full dataset** of 3fb^{-1}:

Coefficient $\mathcal{C}_i^{NP} = \mathcal{C}_i - \mathcal{C}_i^{SM}$	Best fit	1σ	3σ	Pull_{SM}
$\mathcal{C}_7^{\rm NP}$	-0.02	$[-0.04, -0.00]$	$[-0.07, 0.03]$	1.2
$\mathcal{C}_9^{\rm NP}$	-1.09	$[-1.29, -0.87]$	$[-1.67, -0.39]$	**4.5** $\Leftarrow$
$\mathcal{C}_{10}^{\rm NP}$	0.56	$[0.32, 0.81]$	$[-0.12, 1.36]$	2.5
$\mathcal{C}_{7'}^{\rm NP}$	0.02	$[-0.01, 0.04]$	$[-0.06, 0.09]$	0.6
$\mathcal{C}_{9'}^{\rm NP}$	0.46	$[0.18, 0.74]$	$[-0.36, 1.31]$	1.7
$\mathcal{C}_{10'}^{\rm NP}$	-0.25	$[-0.44, -0.06]$	$[-0.82, 0.31]$	1.3
$\mathcal{C}_9^{\rm NP} = \mathcal{C}_{10}^{\rm NP}$	-0.22	$[-0.40, -0.02]$	$[-0.74, 0.50]$	1.1
$\mathcal{C}_9^{\rm NP} = -\mathcal{C}_{10}^{\rm NP}$	-0.68	$[-0.85, -0.50]$	$[-1.22, -0.18]$	**4.2** $\Leftarrow$
$\mathcal{C}_9^{\rm NP} = -\mathcal{C}_{9'}^{\rm NP}$	-1.06	$[-1.25, -0.86]$	$[-1.60, -0.40]$	4.8 (low recoil)
$\mathcal{C}_9^{\rm NP} = -\mathcal{C}_{10}^{\rm NP} = -\mathcal{C}_{9'}^{\rm NP} = -\mathcal{C}_{10'}^{\rm NP}$	-0.69	$[-0.89, -0.51]$	$[-1.37, -0.16]$	4.1

Impact on the anomalies of a contribution from NP $C_9^{NP} = -1.1$

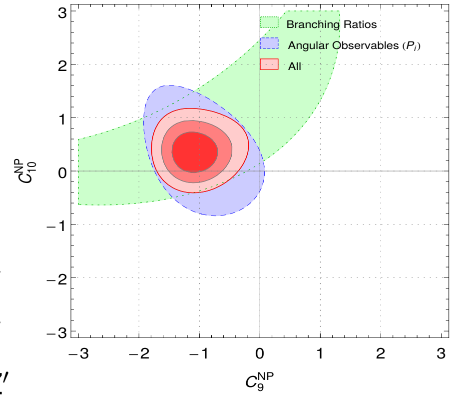


(1),(2) and (3) use 3 fb^{-1} dataset and latest theory prediction for SM (gray) and NP ($C_9^{NP} = -1.1$).

All anomalies and tensions gets solved or alleviated with $C_9^{NP} \sim \mathcal{O}(-1)$

Result of the fit with 2D Wilson coefficient constrained and unconstrained

Coefficient	Best Fit Point	$\mathrm{Pull}_{\mathrm{SM}}$	
$(\mathcal{C}_7^{\mathrm{NP}}, \mathcal{C}_9^{\mathrm{NP}})$	$(-0.00, -1.07)$	**4.1**	
$(\mathcal{C}_9^{\mathrm{NP}}, \mathcal{C}_{10}^{\mathrm{NP}})$	$(-1.08, 0.33)$	**4.3**	
$(\mathcal{C}_9^{\mathrm{NP}}, \mathcal{C}_{7'}^{\mathrm{NP}})$	$(-1.09, 0.02)$	**4.2**	
$(\mathcal{C}_9^{\mathrm{NP}}, \mathcal{C}_{9'}^{\mathrm{NP}})$	$(-1.12, 0.77)$	**4.5**	
$(\mathcal{C}_9^{\mathrm{NP}}, \mathcal{C}_{10'}^{\mathrm{NP}})$	$(-1.17, -0.35)$	**4.5**	
$(\mathcal{C}_9^{\mathrm{NP}} = -\mathcal{C}_{9'}^{\mathrm{NP}}, \mathcal{C}_{10}^{\mathrm{NP}} = \mathcal{C}_{10'}^{\mathrm{NP}})$	$(-1.15, 0.34)$	**4.7**	no-Z'
$(\mathcal{C}_9^{\mathrm{NP}} = -\mathcal{C}_{9'}^{\mathrm{NP}}, \mathcal{C}_{10}^{\mathrm{NP}} = -\mathcal{C}_{10'}^{\mathrm{NP}})$	$(-1.06, 0.06)$	**4.4**	Z'
$(\mathcal{C}_9^{\mathrm{NP}} = \mathcal{C}_{9'}^{\mathrm{NP}}, \mathcal{C}_{10}^{\mathrm{NP}} = \mathcal{C}_{10'}^{\mathrm{NP}})$	$(-0.64, -0.21)$	3.9	Z'
$(\mathcal{C}_9^{\mathrm{NP}} = -\mathcal{C}_{10}^{\mathrm{NP}}, \mathcal{C}_{9'}^{\mathrm{NP}} = \mathcal{C}_{10'}^{\mathrm{NP}})$	$(-0.72, 0.29)$	3.8	no-Z'

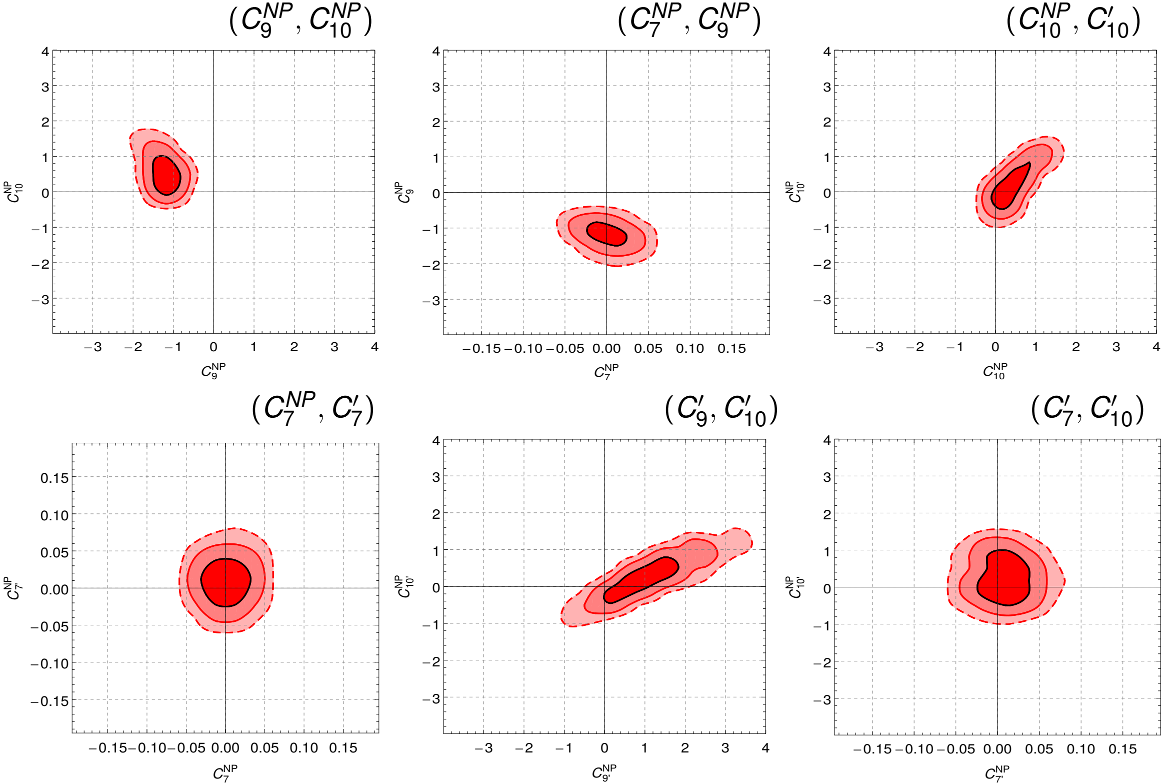


- C_9^{NP} always play a dominant role
- All 2D scenarios above 4σ are quite indistinguishable. We have done a systematic work to check what are the most relevant Wilson Coefficients to explain all deviations, by allowing progressively different WC to get NP contributions and compare the pulls.

Result of the fit to the SIX Wilson coefficients free

Coefficient	1σ	2σ	3σ	
$\mathcal{C}_7^{\rm NP}$	$[-0.02, 0.03]$	$[-0.04, 0.04]$	$[-0.05, 0.08]$	• no preference
$\mathcal{C}_9^{\rm NP}$	$[-1.4, -1.0]$	$[-1.7, -0.7]$	$[-2.2, -0.4]$	• **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 preference
$\mathcal{C}_{9'}^{\rm NP}$	$[0.3, 1.8]$	$[-0.5, 2.7]$	$[-1.3, 3.7]$	• positive
$\mathcal{C}_{10'}^{\rm NP}$	$[-0.3, 0.9]$	$[-0.7, 1.3]$	$[-1.0, 1.6]$	• $\sim$ positive

- C_9 is consistent with SM only **above 3**σ
- All other are consistent with zero at 1σ except for C_9' (at 2 σ).
- The Pull$_{SM}$ for the 6D fit is 3.6σ.


(C_9^{NP}, C_{10}^{NP})
(C_7^{NP}, C_9^{NP})
(C_{10}^{NP}, C'_{10})
(C_7^{NP}, C'_7)
(C'_9, C'_{10})
(C'_7, C'_{10})
C_9^{NP}
C_{10}^{NP}
C_7^{NP}
$C_{10'}^{NP}$
$C_{7'}^{NP}$
$C_{9'}^{NP}$

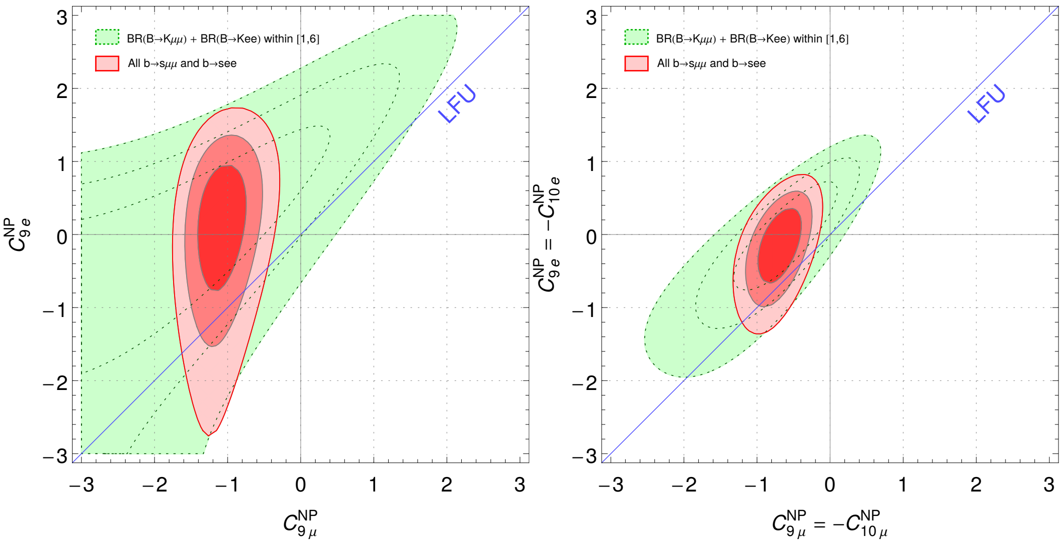
Impact of $B \to Ke^+e^-$ under hypothesis of maximal Lepton Flavour Universal Violation

1D-Coefficient	Best fit	1σ	3σ	Pull_{SM}
$\mathcal{C}_9^{\text{NP}}$	-1.11	$[-1.31, -0.90]$	$[-1.67, -0.46]$	**4.5 → 4.9**
$\mathcal{C}_9^{\text{NP}} = -\mathcal{C}_{10}^{\text{NP}}$	-0.65	$[-0.80, -0.50]$	$[-1.13, -0.21]$	**4.2 → 4.6**
$\mathcal{C}_9^{\text{NP}} = -\mathcal{C}_{9'}^{\text{NP}}$	-1.07	$[-1.25, -0.86]$	$[-1.60, -0.42]$	4.9
$\mathcal{C}_9^{\text{NP}} = -\mathcal{C}_{10}^{\text{NP}} = -\mathcal{C}_{9'}^{\text{NP}} = -\mathcal{C}_{10'}^{\text{NP}}$	-0.66	$[-0.84, -0.50]$	$[-1.25, -0.20]$	**4.1 → 4.5**

2D-Coefficient	Best Fit Point	Pull_{SM}
$(C_7^{\text{NP}}, C_9^{\text{NP}})$	$(-0.00, -1.10)$	**4.1 → 4.6**
$(C_9^{\text{NP}}, C_{10}^{\text{NP}})$	$(-1.06, 0.33)$	**4.3 → 4.8**
$(C_9^{\text{NP}}, C_{7'}^{\text{NP}})$	$(-1.16, 0.02)$	**4.2 → 4.7**
$(C_9^{\text{NP}}, C_{9'}^{\text{NP}})$	$(-1.15, 0.64)$	**4.5 → 4.9**
$(C_9^{\text{NP}}, C_{10'}^{\text{NP}})$	$(-1.23, -0.29)$	**4.5 → 4.9**
$(C_9^{\text{NP}} = -C_{9'}^{\text{NP}}, C_{10}^{\text{NP}} = C_{10'}^{\text{NP}})$	$(-1.18, 0.38)$	**4.7 → 5.1**
$(C_9^{\text{NP}} = -C_{9'}^{\text{NP}}, C_{10}^{\text{NP}} = -C_{10'}^{\text{NP}})$	$(-1.11, 0.04)$	**4.5**
$(C_9^{\text{NP}} = C_{9'}^{\text{NP}}, C_{10}^{\text{NP}} = C_{10'}^{\text{NP}})$	$(-0.64, -0.11)$	**3.9 → 4.3**
$(C_9^{\text{NP}} = -C_{10}^{\text{NP}}, C_{9'}^{\text{NP}} = C_{10'}^{\text{NP}})$	$(-0.69, 0.27)$	**3.8 → 4.2**

- The strong correlations among form factors of $B \to K\mu\mu$ and $B \to Kee$ assuming no NP in $B \to Kee$ enhances the NP evidence in muons.
- Notice that we use all bins in $B \to K\mu\mu$ while R_K is only [1,6]. **All theory correlations included**.
- Only scenarios explaining R_K get an extra enhancement of +0.4-0.5 σ

Fits considering Lepton Flavour (non-) Universality



- If NP-LFUV is assumed, NP may enter both $b \to see$ and $b \to s\mu\mu$ decays with different values.

$\Rightarrow$ For each scenario, we see that there is no clear indication of a NP contribution in the electron sector, whereas one has clearly a non-vanishing contribution for the muon sector, with a deviation from the Lepton Flavour Universality line.

How much the fit results depend on the details?

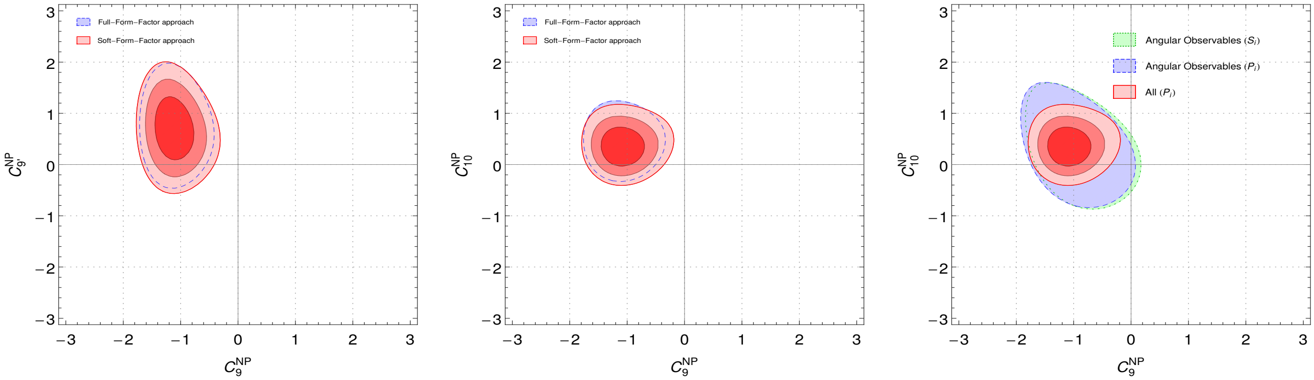


Figure: *We show the 3 σ regions allowed using form factors in BSZ'15 in the full form factor approach (long-dashed blue) compared to our reference fit with the soft form factor approach (red, with 1,2,3 σ contours).*

- The results of the fit using (IQCDF-KMPW) or (Full-FF-BSZ) and/or different set of observables are perfectly consistent once all correlations are included. But the individual observables...

anomaly [4,6] bin	P_5' error SIZE [pull]	S_5 error SIZE [pull]
Full-FF-**BSZ** (1503.05534)	8.6% [2.7σ]	12% [2.0σ]
IQCDF-**KMPW** (1510.04239)	10% [2.9σ]	40% [1.2σ]

Theoretical description of $B \to K^*\mu\mu$

at low-q^2 in a nutshell:

systematic treatment of hadronic uncertainties

Theoretical description of $B \to K^* \ell^+ \ell^-$ @ low-q^2

Improved-QCDF approach: QCDF+exploit **symmetry relations** at large-recoil (limit) among FF:

$$\frac{m_B}{m_B+m_{K^*}} \mathbf{V}(\mathbf{q^2}) = \frac{m_B+m_{K^*}}{2E} \mathbf{A_1}(\mathbf{q^2}) = \mathbf{T_1}(\mathbf{q^2}) = \frac{m_B}{2E} \mathbf{T_2}(\mathbf{q^2}) = \xi_\perp(E)$$

$$\frac{m_{K^*}}{E} \mathbf{A_0}(\mathbf{q^2}) = \frac{m_B+m_{K^*}}{2E} \mathbf{A_1}(\mathbf{q^2}) - \frac{m_B-m_{K^*}}{m_B} \mathbf{A_2}(\mathbf{q^2}) = \frac{m_B}{2E} \mathbf{T_2}(\mathbf{q^2}) - \mathbf{T_3}(\mathbf{q^2}) = \xi_\parallel(E)$$

- Our approach is completed with 4 types of corrections. From a FF decomposition (example):

$$\mathbf{V}(\mathbf{q^2}) = \frac{m_B+m_{K^*}}{m_B} \xi_\perp(q^2) + \Delta V^{\alpha_s}(q^2) + \Delta V^{\Lambda}(q^2)$$

- $\Delta V^{\alpha_s}(q^2)$: Known Factorizable α_s breaking corrections at NLO from QCDF.
- $\Delta V^{\Lambda}(q^2)$: Factorizable power corrections (using a systematic procedure for each FF, see later)

$\Rightarrow$ **IQCDF is Transparent**, valid for **ANY** FF parametrization (BZ, BSZ, **KMPW**,...). **Dominant correlations** automatically implemented in a transparent way via **SYMMETRIES.**

$\Rightarrow$ **Construction of FFI observables $\mathbf{P_i^{(\prime)}}$**: at LO in $1/m_b$, α_s and large-recoil limit (E_K^* large):

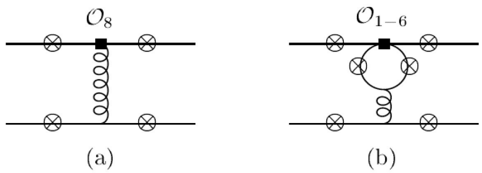
$$A_\perp^{L,R} \propto \xi_\perp \quad A_\parallel^{L,R} \propto \xi_\perp \quad A_0^{L,R} \propto \xi_\parallel$$

QCDF provides a systematic framework to include α_s (factorizable and non-factorizable) corrections.
Amplitude is represented by:

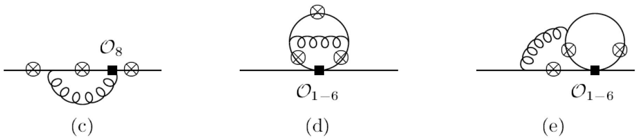
$$\langle \ell^+ \ell^- \bar{K}_a^* | H_{\text{eff}} | \bar{B} \rangle = \mathcal{C}_a \xi_a + \Phi_B \otimes T_a \otimes \Phi_{K^*} \text{ with } a = \perp, \|$$

- Non-factorizable α_s corrections:

⇒ First class: spectator quark in the B meson participates in the hard scattering: (T_a)



⇒ Second class: Matrix elements of four-quark operators and the chromomagnetic dipole op.: ($\mathcal{C}_a$)



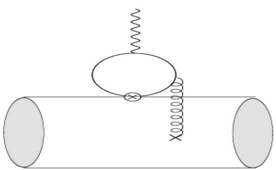
BUT also **we include** a second type of power corrections:

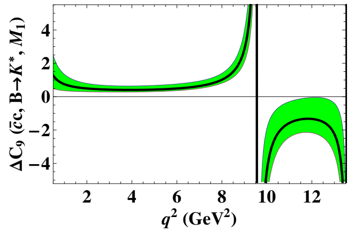
- Non-factorizable power corrections including charm-quark loops.

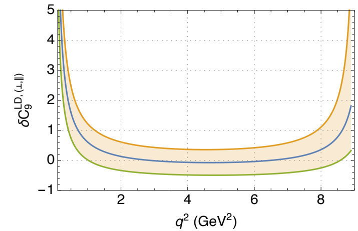
All four (non-)factorizable α_s and power corrections are included in our predictions.

Non-factorizable power corrections

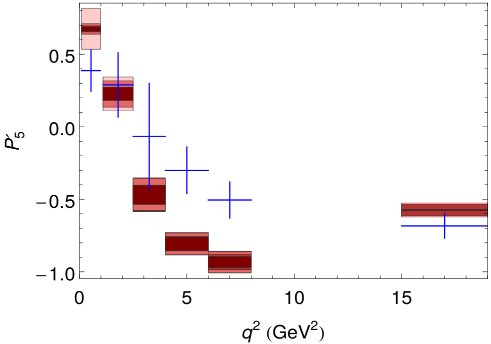
- **Non-factorizable power corrections (amplitudes)**: subleading new unknown non-perturbative. BEYOND SCET/QCDF at leading power in $1/m_b$. Multiply each amplitude $i = 0, \perp, \parallel$ with a complex q^2-dependent factor. $\mathcal{T}_i^{\rm had} \to (1 + r_i(q^2))\, \mathcal{T}_i^{\rm had}$ with $\mathcal{T}_i^{\rm had} = \mathcal{T}_i|_{C_7^{(\prime)} \to 0}$ entering $\langle K^* \gamma^* | H_{eff} | B \rangle$.
- **Charm-loops:** At large-recoil two type of contributions: $\Delta C_9^{BK^*} = \delta C_{9,\rm pert}^{BK(*)} + \mathbf{s_i} \delta C_{9,\rm non\ pert}^{BK(*),i}$
  - Short distance (hard-gluons): $\delta \mathbf{C}_{\mathbf{9},\rm pert}^{\mathbf{BK}(*)}$
    - LO included in $C_9 \to C_9 + Y(q^2)$
    - higher-order corrections via QCDF/HQET.
  - Long distance (soft-gluons): $\delta \mathbf{C}_{\mathbf{9},\rm non\ pert}^{\mathbf{BK}(*),\mathbf{i}}$
    - Only existing computation KMPW'10 using LCSR.
    - Partial computation yields $\Delta C_9^{BK^*} > 0$ ($s_i = 1$) $\Rightarrow$ enlarges the anomaly.
      We obtain the LD from KMPW AND allow FOR ANY SIGN $s_i = 0 \pm 1$







Brief Discussion on: P_5' and P_4' (driving the ambulance)



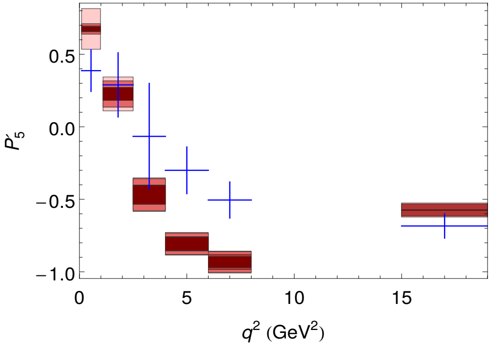
P_5' was proposed for the first time in **DMRV, JHEP 1301(2013)048**

$$P_5' = \sqrt{2}\frac{\mathrm{Re}(A_0^L A_\perp^{L*} - A_0^R A_\perp^{R*})}{\sqrt{|A_0|^2(|A_\perp|^2 + |A_\parallel|^2)}} = \sqrt{2}\frac{\mathrm{Re}[n_0 n_\perp^\dagger]}{\sqrt{|n_0|^2(|n_\perp|^2 + |n_\parallel|^2)}} .$$

with $n_0 = (A_0^L, A_0^{R*})$, $n_\perp = (A_\perp^L, -A_\perp^{R*})$ and $n_\parallel = (A_\parallel^L, A_\parallel^{R*})$

- If no-RHC $|n_\perp| \simeq |n_\parallel|$ $(H_{+1} \simeq 0) \Rightarrow P_5' \propto \cos\theta_{\mathbf{0},\perp}(\mathbf{q^2})$

Brief Discussion on: P_5' and P_4' (driving the ambulance)



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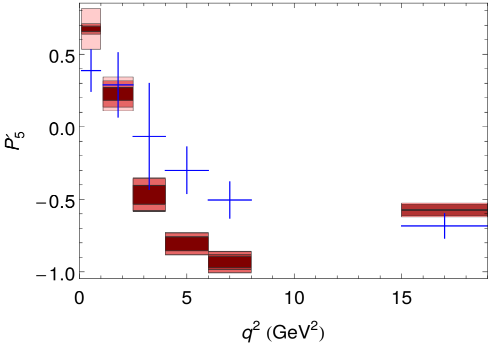
- If no-RHC $|n_\perp| \simeq |n_\parallel|$ $(H_{+1} \simeq 0) \Rightarrow P_5' \propto \cos\theta_{\mathbf{0},\perp}(\mathbf{q^2})$

In the large-recoil limit with no RHC

$$A^L_{\perp,\parallel} \propto (1,-1)\left[\mathcal{C}_9^{\rm eff} - \mathcal{C}_{10} + \frac{2\hat{m}_b}{\hat{s}}\mathcal{C}_7^{\rm eff}\right]\xi_\perp(E_{K^*}) \qquad A^R_{\perp,\parallel} \propto (1,-1)\left[\mathcal{C}_9^{\rm eff} + \mathcal{C}_{10} + \frac{2\hat{m}_b}{\hat{s}}\mathcal{C}_7^{\rm eff}\right]\xi_\perp(E_{K^*})$$

$$A_0^L \propto -\left[\mathcal{C}_9^{\rm eff} - \mathcal{C}_{10} + 2\hat{m}_b\mathcal{C}_7^{\rm eff}\right]\xi_\parallel(E_{K^*}) \quad A_0^R \propto -\left[\mathcal{C}_9^{\rm eff} + \mathcal{C}_{10} + 2\hat{m}_b\mathcal{C}_7^{\rm eff}\right]\xi_\parallel(E_{K^*})$$

- In SM $\mathcal{C}_9^{SM} + \mathcal{C}_{10}^{SM} \simeq 0 \to |A^R_{\perp,\parallel}| \ll |A^L_{\perp,\parallel}|$
- **In P_5': If $C_9^{NP} < 0$ then** $A^R_{0,\parallel}\uparrow$, $|A^R_\perp|\uparrow$ and $|A^L_{0,\parallel}|\downarrow$, $A^L_\perp\downarrow$ and due to $-$, $|P_5'|$ gets **strongly** reduced.



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with $n_0 = (A_0^L, A_0^{R*})$, $n_\perp = (A_\perp^L, -A_\perp^{R*})$ and $n_\parallel = (A_\parallel^L, A_\parallel^{R*})$

- If no-RHC $|n_\perp| \simeq |n_\parallel|$ $(H_{+1} \simeq 0) \Rightarrow P_5' \propto \cos\theta_{\mathbf{0},\perp}(\mathbf{q^2})$

In the large-recoil limit with no RHC

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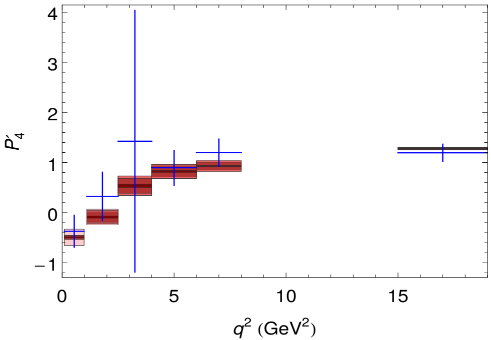
$$A_0^L \propto -\left[\mathcal{C}_9^{\rm eff} - \mathcal{C}_{10} + 2\hat{m}_b\mathcal{C}_7^{\rm eff}\right]\xi_\parallel(E_{K^*}) \quad A_0^R \propto -\left[\mathcal{C}_9^{\rm eff} + \mathcal{C}_{10} + 2\hat{m}_b\mathcal{C}_7^{\rm eff}\right]\xi_\parallel(E_{K^*})$$

- In SM $\mathcal{C}_9^{SM} + \mathcal{C}_{10}^{SM} \simeq 0 \to |A_{\perp,\parallel}^R| \ll |A_{\perp,\parallel}^L|$
- **In P_5':** If $C_9^{NP} < 0$ then $A_{0,\parallel}^R \uparrow$, $|A_\perp^R| \uparrow$ and $|A_{0,\parallel}^L| \downarrow$, $A_\perp^L \downarrow$ and due to $-$, $|P_5'|$ gets **strongly** reduced.

Brief Discussion on: P_5' and P_4'



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$$P_4' = \sqrt{2}\frac{\mathrm{Re}(A_0^L A_\|^{L*} + A_0^R A_\|^{R*})}{\sqrt{|A_0|^2(|A_\perp|^2 + |A_\||^2)}} = \sqrt{2}\frac{\mathrm{Re}[n_0 n_\|^\dagger]}{\sqrt{|n_0|^2(|n_\perp|^2 + |n_\||^2)}}.$$

with $n_0 = (A_0^L, A_0^{R*})$, $n_\perp = (A_\perp^L, -A_\perp^{R*})$ and $n_\| = (A_\|^L, A_\|^{R*})$

- If no-RHC $|n_\perp| \simeq |n_\|| \; (H_{+1} \simeq 0) \Rightarrow P_4' \propto \cos\theta_{\mathbf{0},\|}(\mathbf{q^2})$

In the large-recoil limit with no RHC

$$A_{\perp,\|}^L \propto (1,-1)\left[\mathcal{C}_9^{\rm eff} - \mathcal{C}_{10} + \frac{2\hat{m}_b}{\hat{s}}\mathcal{C}_7^{\rm eff}\right]\xi_\perp(E_{K^*}) \qquad A_{\perp,\|}^R \propto (1,-1)\left[\mathcal{C}_9^{\rm eff} + \mathcal{C}_{10} + \frac{2\hat{m}_b}{\hat{s}}\mathcal{C}_7^{\rm eff}\right]\xi_\perp(E_{K^*})$$

$$A_0^L \propto -\left[\mathcal{C}_9^{\rm eff} - \mathcal{C}_{10} + 2\hat{m}_b\mathcal{C}_7^{\rm eff}\right]\xi_\|(E_{K^*}) \quad A_0^R \propto -\left[\mathcal{C}_9^{\rm eff} + \mathcal{C}_{10} + 2\hat{m}_b\mathcal{C}_7^{\rm eff}\right]\xi_\|(E_{K^*})$$

- In SM $\mathcal{C}_9^{SM} + \mathcal{C}_{10}^{SM} \simeq 0 \to |A_{\perp,\|}^R| \ll |A_{\perp,\|}^L|$
- **In** P_4' :If $C_9^{NP} < 0$ then $A_{0,\|}^R \uparrow$, $|A_\perp^R| \uparrow$ and $|A_{0,\|}^L| \downarrow$, $A_\perp^L \downarrow$ due to $+$ what L loses R gains (little change).

Are the hadronic uncertainties correctly estimated?

Pedagogical **deconstruction** of wrong arguments

Discussion of wrong arguments from 3 papers:

Lyon-Zwicky, arXiv: **1406.0566** (**LZ'14**)
Jaeger-Camalich, arXiv: **1412.3183** (**JC'14**)
Ciuchini-Silvestrini-Valli et al. arXiv: **1512.07157** (**CFFMPSV'15**)

What are Factorizable power corrections and how they emerge?

Appear when expressing the full form factor in a soft form factor piece + corrections:

$$F^{full}(q^2) = F^{\rm soft}(\xi_{\perp,\|}(q^2)) + \Delta F^{\alpha_s}(q^2) + \Delta F^{\Lambda} \quad \text{with} \quad \Delta F^{\Lambda} = a_F + b_F \frac{q^2}{m_B^2} + c_F \frac{q^4}{m_B^4}$$

How one can obtain power corrections?

(DHMV'14)

ΔF^{Λ} is obtained from a fit in $q^2/m_B^2 \Rightarrow$ central values a_F, b_F, c_F.

Errors are taken **uncorrelated** to be $\mathcal{O}(\Lambda/m_b) \times \mathrm{FF} \simeq 0.1\mathrm{FF}$.

Why? to minimize sensitivity/dependence on FF computational details.

	$\hat{a}_F^{(1)}$	$\hat{b}_F^{(1)}$	$\hat{c}_F^{(1)}$	$r(0\,\mathrm{GeV}^2)$	$r(4\,\mathrm{GeV}^2)$	$r(8\,\mathrm{GeV}^2)$
A_1(KMPW)	-0.01 ± 0.03	-0.06 ± 0.02	0.16 ± 0.02	5%	6%	5%
A_1(BZ)	-0.01 ± 0.03	0.04 ± 0.02	0.08 ± 0.02	3%	1%	3%

$r = (a_F + b_F q^2/m_B^2 + c_F q^4/m_B^4)/FF(q^2)$ is the percentage of p.c. found to be $\leq 10\%$

$\rightarrow$ Later on JC'14 followed same strategy

and considered also uncorrelated errors but central values were set to zero.

What do they missed in JC'14?

In JC'14: *It is wrongly assumed that* **their prediction** *of an observable like P_5' is scheme independent.*

Scheme choice here means the way $\xi_{\perp,\|}$ are fixed to all orders in terms of full FF. Example:

$$\xi_\perp^{(1)}(q^2) \equiv \frac{m_B}{m_B+m_{K^*}} V(q^2) \quad \xi_\|^{(1)}(q^2) \equiv \frac{m_B+m_{K^*}}{2E} A_1(q^2) - \frac{m_B-m_{K^*}}{m_B} A_2(q^2), \ \text{(Beneke et al. 05)}$$

or

$$\xi_\perp^{(2)}(q^2) \equiv T_1(q^2), \qquad \xi_\|^{(2)}(q^2) \equiv \frac{m_{K^*}}{E} A_0(q^2). \ \text{(old Beneke et al. 01)}$$

BUT THE CORRECT STATEMENT IS: The prediction of an observable like P_5' is scheme independent if all correlations are included!!! ... unfortunately JC'14 does not include them!!.

Illustrative example (using for instance BSZ):

$\langle P_5'\rangle_{[4,6]}$	error of f.f.+p.c. scheme-1 in transversity basis **DHMV'14**	error of f.f.+p.c. scheme-2 in helicity basis **JC'14**
NO correlations among errors of p.c. (hyp. 10%)	± 0.05	$\pm$**0.12**
WITH correlations among errors of p.c.	± 0.03	± 0.03

FULL FF scheme indep.	± 0.03

Conclusions:

- If power corrections are taken uncorrelated to reduce the sensitivity to details of FF computation, which is fine,**not any arbitrary scheme choice is appropriate.**

A bad scheme's choice like in JC'14 inflated artificially the errors **x 4** in the example

Wrong argument 2: A huge charm-loop or unknown non-factorizable p.c?

Two attempts:

Attempt 1 (Lyon, Zwicky'14 unpublished):

- Using $e^+e^- \to$ hadrons to build a model of $c\bar{c}$ resonances at low-recoil in $B \to K\mu\mu$.
  Conceptual problem: **extrapolate result** at large-recoil and assume it holds the same for $B \to K^*\mu\mu$.

$\Rightarrow$ **Interesting observation:** Phase of helicity amplitudes $e^{i\delta_{J/\Psi K^*}}$ from $\delta_{J/\Psi K^*} \simeq 0$ (KMPW) to π
$\to$ we introduce s_i.

Attempt 2 (Ciuchini, Fedele, Franco, Mishima, Paul, Silvestrini, Valli'15 -CFFMPSV):

- Introduce a fully arbitrary parametrization for non-factorizable power correction:

$$H_\lambda \to H_\lambda + h_\lambda \text{ where } h_\lambda = h_\lambda^{(0)} + h_\lambda^{(1)} q^2 + h_\lambda^{(2)} q^4 \qquad \text{and} \quad h_\lambda^{(0)} \to C_7^{NP}, h_\lambda^{(1)} \to C_9^{\rm NP}$$

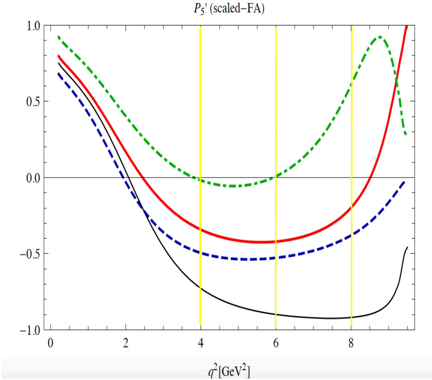
with $(\lambda = 0, \pm)$ (copied from JC'14).
Fundamental problems: complete lack of theory input/output $\Rightarrow$ **no predictivity** with 18 free parameters (any shape). **Specific problems...**

$C_9 - C_9^{SM} \simeq$ constant+KMPW **similar to us!!**. So what is this constant $C_9^{\rm NP}$ or $h_\lambda^{(1)}$?

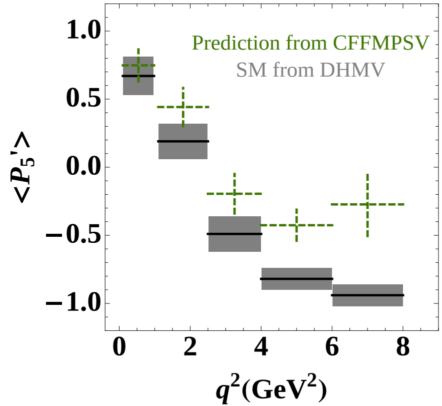
(CAUTION: They only considered one part of the data $B \to K^*\mu\mu$ at large-recoil)

1. BOTH LZ'14 and CFFMPSV'15 share some problem, they exhibit the **same uptrend behaviour**:
Predict $\langle P_5' \rangle_{[6,8]}$ to be above $\langle P_5' \rangle_{[4,6]}$ but data favours the opposite (more significance needed)

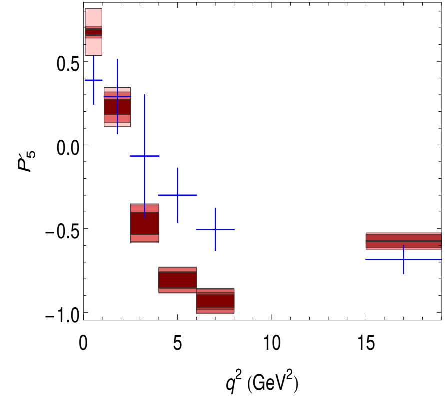
Lyon-Zwicky'14



Ciuchini-Silvestrini-Valli et al.'15



Data (blue) and DHMV (red).



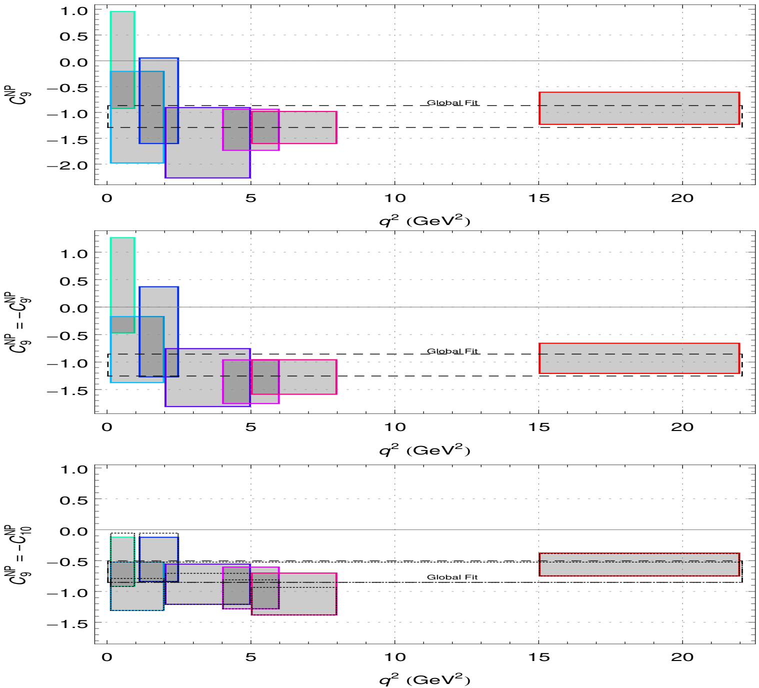
Different hypothesis (colors RBG)

From Table 6 of predictions'

Descending trend of data.

2. If the answer would be unknown $h_\lambda^{(i)}$ you cannot explain many data, while $C_9^{NP} = -1.1$ can:

- nor R_K (solved with $C_9^{NP} = -1.1$) neither any future LFVU observable like R_{K^*} due to charm universality.
- any tiny tension in the low-recoil region of $B^0 \to K^{*0}\mu\mu$ ($1.7 \to 0.3\sigma$), $B^+ \to K^{*+}\mu\mu$ ($2.5 \to 1.2\sigma$), $B_s \to \phi\mu\mu$ ($2.3 \to 0.5\sigma$) cannot be explained.
- Also the old bin [2,4.3] of P_2 of 2013 is difficult to explain by charm.



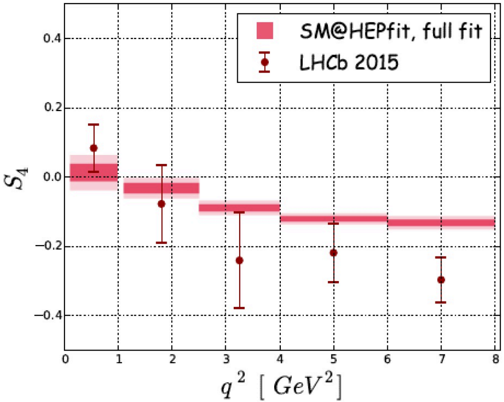
Result of bin-by-bin analysis of C_9 in 3 scenarios.

- **Notice the excellent agreement of bins [2,5], [4,6], [5,8].** *Strong argument in favour of including the [5,8] region-bin.*
- **First bin is afflicted by lepton-mass effects.** (see Back-up slides)
- **We do not find indication for a q^2-dependence in C_9 neither in the plots nor in a 6D fit adding $a^i + b^i s$ to $C_9^{\rm eff}$ for $i = K^*, K, \phi$.**
  $\rightarrow$ disfavours again charm explanation.
- 2nd and 3rd plots test if you allow for NP in other WC the agreement of C_9 bin by bin improves as compared to 1st plot.

Contradictory statements:

3. "*No deviation is present once all the theoretical uncertainties are taken into account*".

$\Rightarrow$ Indeed they have a (**2.7**σ) deviation in S_4, a fully SM-like observable for us (us and also BSZ find good agreement with SM in all bins! **See table from DHMV'15**)



$S_4(B \to K^* \mu^+ \mu^-)$	Standard Model	Experiment	Pull
[0.1, 0.98]	-0.08 ± 0.05	-0.08 ± 0.07	-0.0
[1.1, 2.5]	-0.01 ± 0.03	0.08 ± 0.11	-0.8
[2.5, 4]	0.11 ± 0.07	0.23 ± 0.14	-0.8
[4, 6]	0.18 ± 0.08	0.22 ± 0.09	-0.3
[6, 8]	0.22 ± 0.07	0.30 ± 0.07	-0.8
[15, 19]	0.30 ± 0.01	0.28 ± 0.04	$+0.5$

4. Symmetries transformations of $A_{\perp,\|,0}$ led to a **consistency relation**: [Serra-Matias'14]

$$P_2^{rel} = \frac{1}{2}\left[P_4' P_5' + \delta_a + \frac{1}{\beta}\sqrt{(-1+P_1+P_4'^2)(-1-P_1+\beta^2 P_5'^2)+\delta_b}\right] \qquad P_i \to \langle P_i \rangle\ (\Delta)$$

where δ_a and δ_b are function of product of tiny P_6', P_8', P_3.

This **must hold** *independently of any crazy non-factorizable, factorizable, or New Physics (with no weak phases $P_i^{CP}=0$ or new scalars) that is included inside the H_λ (or $A_{\perp,\|,0}$)*

Example: $\Rightarrow$ Using theory predictions (DHMV'15) for **bin [4,6]** one has:

$$\langle P_1 \rangle = 0.03 \quad \langle P_4' \rangle = +0.82 \quad \langle P_5' \rangle = -0.82 \quad \langle P_2 \rangle = -\mathbf{0.18}$$

consistency relation $\Rightarrow \langle P_2 \rangle^{rel} = -\mathbf{0.17}$ ($\Delta = \mathbf{0.01}$ from binning). Perfect agreement. If $A_{\rm FB} = f(F_L, S_i)$

		$CFFMPSV_{predictions}$	$CFFMPSV_{full\ fit}$	SM-BSZ ($\delta_i = 0$)	SM-DHMV
[4, 6]	$\langle A_{\rm FB} \rangle^{rel}$	$-\mathbf{0.14 \pm 0.04}$	$-\mathbf{0.16 \pm 0.03}$	$+0.11 \pm 0.05$	$+0.05 \pm 0.19$
	$\langle A_{\rm FB} \rangle$	$+\mathbf{0.05 \pm 0.04 \Rightarrow 3.4\sigma}$	$+\mathbf{0.04 \pm 0.03 \Rightarrow 4.7\sigma}$	$+0.12 \pm 0.04 \Rightarrow \mathbf{0.2\sigma}$	$+0.08 \pm 0.11 \Rightarrow \mathbf{0.1\sigma}$
[6, 8]	$\langle A_{\rm FB} \rangle^{rel}$	-0.27 ± 0.08	-0.15 ± 0.05	$--$	$+0.17 \pm 0.18$
	$\langle A_{\rm FB} \rangle$	$+0.12 \pm 0.08 \Rightarrow 3.4\sigma$	$+0.13 \pm 0.03 \Rightarrow 4.8\sigma$	$--$	$+0.21 \pm 0.21 \Rightarrow \mathbf{0.1\sigma}$

They are now recomputing all their tables of predictions for the observables ...

Possible New Physics explanations?

Let's start with what it cannot be....

First estimates of different models shows:

$\Rightarrow$ **difficulties to generate a large negative contribution to C_9**

- **Minimal Supersymmetric Model cannot generate a large NEGATIVE C_9^{NP}:**
  - Z-penguins: small vector coupling to charged leptons $\propto 1 - 4s_W^2 \simeq 0.1$
  - Photon-penguins:
    - Charged Higgs: suppressed by $tan\beta$ but even for $tan\beta \sim 1$ (for $m_H^\pm > 100$ GeV) is too small.
    - Higgsino and gaugino loops: any large contribution is in tension with direct searches.
  - Box-diagrams induced also from charged Higgs, Higgsino, and gaugino loops. All contributions are negligible due to muon Yukawa couplings or in tension with direct searches.

On the contrary a Z' in the range 1-3 TeV (depending on its couplings) could explain it...

Possible New Physics explanations?

Let's start with what it cannot be....

First estimates of different models shows:

$\Rightarrow$ **difficulties to generate a large negative contribution to C_9**

- **Minimal Supersymmetric Model cannot generate a large NEGATIVE C_9^{NP}:**
  - Z-penguins: small vector coupling to charged leptons $\propto 1 - 4s_W^2 \simeq 0.1$
  - Photon-penguins:
    - Charged Higgs: suppressed by $tan\beta$ but even for $tan\beta \sim 1$ (for $m_H^\pm > 100$ GeV) is too small.
    - Higgsino and gaugino loops: any large contribution is in tension with direct searches.
  - Box-diagrams induced also from charged Higgs, Higgsino, and gaugino loops. All contributions are negligible due to muon Yukawa couplings or in tension with direct searches.

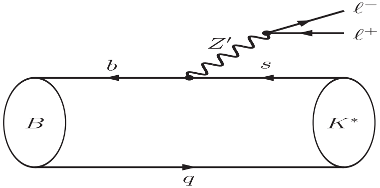
On the contrary a Z' in the range 1-3 TeV (depending on its couplings) could explain it...

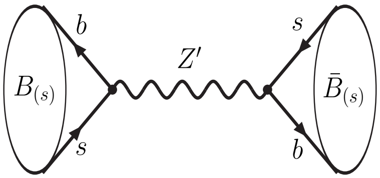
Z' particle a possible explanation?

In [**DMV'13**] we proposed to explain the anomaly in $B \to K^*\mu\mu$ with a Z' **gauge boson** contributing to

$$\mathcal{O}_9 = e^2/(16\pi^2)\,(\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)\,,$$

with specific couplings as a possible explanation of the anomaly in P_5'.





Using the notation of Buras'12,'13

$$\mathcal{L}^q = \left(\bar{s}\gamma_\nu P_L b \Delta_L^{sb} + \bar{s}\gamma_\nu P_R b \Delta_R^{sb} + h.c.\right) Z'^\nu \qquad \mathcal{L}^{lep} = \left(\bar{\mu}\gamma_\nu P_L \mu \Delta_{\mathbf{L}}{}^{\mu\bar{\mu}} + \bar{\mu}\gamma_\nu P_R \mu \Delta_{\mathbf{R}}{}^{\mu\bar{\mu}} + \ldots\right) Z'^\nu$$

The Wilson coefficients of the semileptonic operators are:

$$\mathcal{C}^{\rm NP}_{\{9,10\}} = -\frac{1}{s_W^2 g_{SM}^2}\frac{1}{M_{Z'}^2}\frac{\Delta_L^{sb}\Delta^{\mu\mu}_{\{\mathbf{V},\mathbf{A}\}}}{\lambda_{ts}}\,, \qquad \mathcal{C}^{\rm NP}_{\{9',10'\}} = -\frac{1}{s_W^2 g_{SM}^2}\frac{1}{M_{Z'}^2}\frac{\Delta_R^{sb}\Delta^{\mu\mu}_{\{\mathbf{V},\mathbf{A}\}}}{\lambda_{ts}}\,,$$

with the vector and axial couplings to muons: $\Delta^{\mu\mu}_{\mathbf{V},\mathbf{A}} = \Delta^{\mu\mu}_{\mathbf{R}} \pm \Delta^{\mu\mu}_{\mathbf{L}}$.

Δ_L^{sb} with same phase as $\lambda_{ts} = V_{tb}V_{ts}^*$ (to avoid ϕ_s) like in MFV. Main constraint from ΔM_{B_s} ($\Delta^{sb}_{L,R}$).

A Z' model can belong to the following categories:

	no-coupling	non-zero couplings	Pull_{SM}
C_9	**no**-right-handed quark & no-muon-axial coupling	$\Delta_L^{sb} \neq 0$, $\Delta_V^{\mu\mu} \neq 0$	4.9σ
(C_9, C_{10})	**no**-right-handed quark coupling	$\Delta_L^{sb} \neq 0$, $\Delta_V^{\mu\mu} \neq 0$, $\Delta_A^{\mu\mu} \neq 0$	4.8σ
(C_9, C_9')	**no**-muon-axial coupling	$\Delta_L^{sb} \neq 0$, $\Delta_R^{sb} \neq 0$,, $\Delta_V^{\mu\mu} \neq 0$	4.9σ
(C_{10}, C_{10}')	**no**-muon-vector coupling	$\Delta_L^{sb} \neq 0$, $\Delta_R^{sb} \neq 0$, $\Delta_A^{\mu\mu} \neq 0$	...
(C_9', C_{10}')	**no**-left-handed quark coupling	$\Delta_R^{sb} \neq 0$, $\Delta_V^{\mu\mu} \neq 0$, $\Delta_A^{\mu\mu} \neq 0$	...

Example: $C_9^{\rm NP} = -1.1$, $\Delta_V^{\mu\mu}/M_Z' = -0.6$ TeV^{-1} and $\Delta_L^{bs}/M_Z' = 0.003$ TeV^{-1}

- If NP enters **all** four semileptonic coefficients, the following relationships hold:

$$\frac{\mathcal{C}_9^{\rm NP}}{\mathcal{C}_{10}^{\rm NP}} = \frac{\mathcal{C}_{9'}^{\rm NP}}{\mathcal{C}_{10'}^{\rm NP}} = \frac{\Delta_V^{\mu\mu}}{\Delta_A^{\mu\mu}}, \qquad \frac{\mathcal{C}_9^{\rm NP}}{\mathcal{C}_{9'}^{\rm NP}} = \frac{\mathcal{C}_{10}^{\rm NP}}{\mathcal{C}_{10'}^{\rm NP}} = \frac{\Delta_L^{sb}}{\Delta_R^{sb}}.$$

Many ongoing attempts to embed this kind of Z' inside a model [U.Haisch, W.Altmannshofer, A.Buras, D. Straub,..]

Also leptoquarks are another option...

The future is bright.... the following 9 months can bring important news...

New Universal LFV observables

Besides adding more statistics in

$$R_K = \frac{\mathrm{Br}(B \to K\mu^+\mu^-)}{\mathrm{Br}(B \to Ke^+e^-)}$$

Several new universal lepton flavour may be coming soon:

$$R_{K^*} = \frac{\mathrm{Br}(B \to K^*\mu^+\mu^-)}{\mathrm{Br}(B \to K^*e^+e^-)} \qquad R_\phi = \frac{\mathrm{Br}(B_s \to \phi\mu^+\mu^-)}{\mathrm{Br}(B_s \to \phi e^+e^-)}$$

Even more interesting is a promising new family of observables that we will present in few weeks.... stay tuned.

Notice that none of the previous measurements if different from 1 **can be explained by charm** *and that significances can go in the range 5-6σ with these new observables...*

And CMS and ATLAS announced in 2015 their analysis of $B \to K^*\mu\mu$ (P_5') to be released soon...

Prediction for LFU tests observables

	$R_K[1,6]$	$R_{K^*}[1.1,6]$	$R_\phi[1.1,6]$
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
$\mathcal{C}_9^{\rm NP} = -\mathcal{C}_{9'}^{\rm NP} = -1.17$, $\mathcal{C}_{10}^{\rm NP} = \mathcal{C}_{10'}^{\rm NP} = 0.26$	0.88 ± 0.01	0.76 ± 0.12 $[0.71 \pm 0.04]$	0.71 ± 0.03

Table: *Predictions for R_K, R_{K^*}, R_ϕ at the best fit point of different scenarios of interest, assuming that NP enters only in the muon sector, and using the inputs of our reference fit, in particular the KMPW form factors for $B \to K$ and $B \to K^*$, and BSZ for $B_s \to \phi$. In brackets the predictions using the form factors in BSZ.*

The relative ordering once measured may help in disentangling some scenarios

Having established with high significance a New Physics contribution to C_9^{NP} what about C_{10}^{NP}?

$\mathcal{B}_{B_s\to\mu\mu}$ is an excellent observable to measure $C_{10} - C'_{10}$, but this can be nicely complemented:

From large-recoil expression:

$$P_2 = \frac{1}{\mathcal{N}}\left\{C_{10} s\left(2C_7^{\text{eff}}\mathbf{m_b m_B} + \text{Re}\left[C_9^{\text{eff}}\right]\mathbf{s}\right) - C'_{10} s\left(2C'_7 m_b m_B + C_9^{\prime\text{eff}} s\right)\right\}$$

where

$$\begin{aligned}\mathcal{N} = \quad & +4\left(C_7^{\text{eff}\,2} + C_7^{\prime\text{eff}\,2}\right) m_b^2 m_B^2 \\ & +4\left(C_7^{\text{eff}}\text{Re}\left[C_9^{\text{eff}}\right] + C_7^{\prime\text{eff}} C_9^{\prime\text{eff}}\right) m_b m_B s + \left(|C_9^{\text{eff}}|^2 + C_{10}^2 + C_9^{\prime\text{eff}\,2} + C_{10}^{\prime\,2}\right) s^2\end{aligned}$$

In CDHMV'16 we point that **$\mathbf{P_2}$ in the first bin [0.1,0.98]** exhibits unique properties:

- Large sensitivity to C_{10}^{NP} and extra shielding against C_9 in a very safe region.
- Sensitivity to any unknown non-factorizable p.c. hidden in C_9^{eff} is strongly q^2-suppressed.

A $C_{10}^{NP} > 0$ improves agreement between data and SM

Subtilities related to lepton masses have to be considered!

Conclusions

- The global analysis of $b \to s\ell^+\ell^-$ with 3 fb^{-1} dataset **shows that the solution** we proposed in 2013 to solve the anomaly with a contribution $\mathbf{C_9^{\rm NP} \simeq -1}$ **is confirmed** and reinforced.

- The **fit result is very robust** and does not show a significant dependence nor on the theory approach used neither on the observables used once correlations are taken into account.
  $\Rightarrow$ **IQCDF and FULL-FF** are nicely complementary methods.

- We have shown that the **treatment of uncertainties** entering the observables in $B \to K^*\mu\mu$ is indeed **under excellent control** and the **alternative explanations** to New Physics are indeed **not in very solid ground**. We have proven (redressing the reassessing...) :
  - **Factorizable p.c.**: While using power corrections with uncorrelated errors is perfectly fine we have shown that an inadequate scheme's choice (JC'14) inflates artificially errors.
  - **Charm-loops**: They all predict bin [6,8] above [4,6] against data. They cannot explain LFVU. Also fundamental consistency problems detected.

- Near future? Maybe $C_{10}^{\rm NP}$ or the prime coefficients can become significant soon.
  We pointed out an observable particularly clean in this respect.

Thank you

Back-up slides

Fits to magnetic operators $\mathcal{O}_7 - \mathcal{O}_{7'}$ at very low q^2

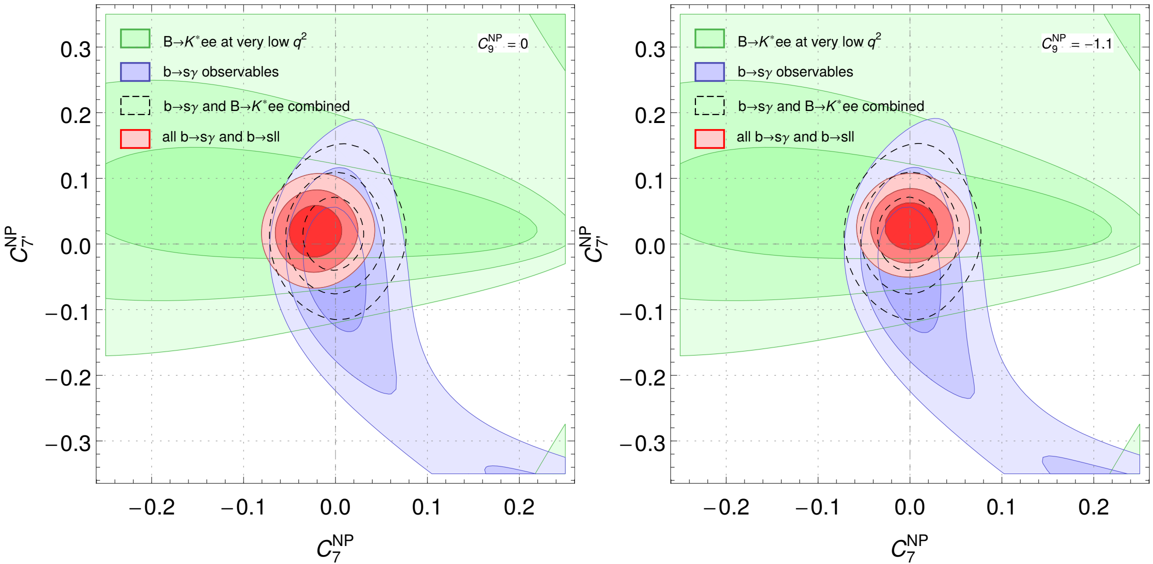
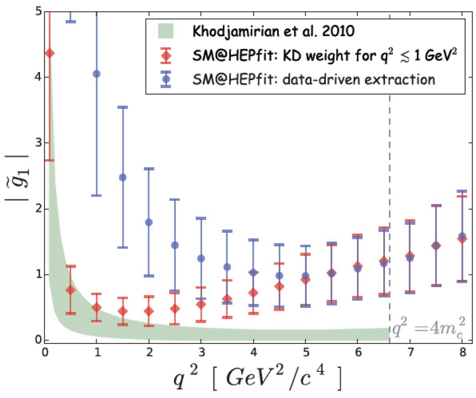


Figure: *Separate fits to $b \to s\gamma$ (blue) and $b \to see$ observables at very low q^2 (green). The combined fit to both sets of data is shown with dashed contours (1,2,3 σ regions). The result of the global fit to all $b \to s\gamma$, $b \to s\ell\ell$ data is shown by the red contours (1,2,3 σ regions). It is assumed that all the other Wilson coefficients have their SM values, except for the plot on the right, where $\mathcal{C}_{9\mu}^{NP} = -1.1$.*

Specific problems of CFFMPSV'15



- $\tilde{g} = \Delta C_9^{non\,pert.}/(2C_1)$
- They force the fit (red points) to agree on the very low-q^2 with KMPW. This has two problems:
  - At very low-q^2 there are other problems **they forgot (lepton mass effects)**.
  - By forcing the fit to agree at very low-q^2 can induce an artificial tilt of your fit.
- More interestingly the blue points where KMPW is not imposed is perfectly compatible with

$C_9 - C_9^{SM} \simeq$ constant+KMPW **similar to us!!**.

So what is this constant $C_9^{\rm NP}$ or $h_\lambda^{(1)}$?

What do they missed in JC'14?

Statement 2: *In JC'14 P_5' is argued to be "accidentally" scheme independent even with uncorrelated p.c:*

In helicity basis we find:

$$P_5' = P_5'|_\infty \Big[1 + \frac{\mathbf{aV}_- - \mathbf{aT}_-}{\xi_\perp} \frac{m_B}{|k|} \frac{m_B^2}{q^2} C_7^{\text{eff}} \frac{C_{9,\perp} C_{9,\parallel} - C_{10}^2}{(C_{9,\perp}^2 + C_{10}^2)(C_{9,\perp} + C_{9,\parallel})} - \frac{\mathbf{aV}_+}{\xi_\perp} \frac{\mathbf{2C_{9,\parallel}}}{\mathbf{C_{9,\perp} + C_{9,\parallel}}}$$
$$+ \frac{aV_0 - aT_0}{\xi_\parallel} 2 C_7^{\text{eff}} \frac{C_{9,\perp} C_{9,\parallel} - C_{10}^2}{(C_{9,\parallel}^2 + C_{10}^2)(C_{9,\perp} + C_{9,\parallel})} + \mathcal{O}\left(\frac{m_{K^*}^2}{m_B^2}, \frac{q^2}{m_B^2}\right)\Big]$$

OK with JC'14 except for the missing term $\mathbf{aV}_+$. Choosing a scheme with $\mathbf{aV}_-$ or $\mathbf{aT}_-$ is equivalent.

ALERT: Only apparently scheme independent in helicity basis for a subset of schemes!

Counterexample: In transversity basis becomes obvious that the choice of scheme matters

$$P_5' = P_5'|_\infty \Big[1 + \frac{\mathbf{aV}}{\xi_\perp} \frac{C_{9,\parallel}}{C_{9,\perp} + C_{9,\parallel}} + \frac{\mathbf{aV} - 2\mathbf{aT_1}}{\xi_\perp} \frac{m_B^2}{q^2} C_7^{\text{eff}} \frac{C_{9,\perp} C_{9,\parallel} - C_{10}^2}{(C_{9,\perp}^2 + C_{10}^2)(C_{9,\perp} + C_{9,\parallel})} - \frac{aA_1}{\xi_\perp} \frac{C_{9,\perp} C_{9,\parallel} + C_{10}^2}{2(C_{9,\perp}^2 + C_{10}^2)} + \ldots$$

The weights of $\mathbf{aV}$ & $\mathbf{aT_1}$ are MANIFESTLY different: $P_5'^{(q^2=6)} = P_5'|_\infty(1 + [\mathbf{0.82}\,\mathbf{aV} - \mathbf{0.24}\,\mathbf{aT_1}]/\xi_\perp(6) + \ldots$

$$\xi_\perp^{(1)}(q^2) \equiv \frac{m_B}{m_B + m_{K^*}} V(q^2) \quad \Rightarrow \mathbf{aV} = 0 \quad or \quad \xi_\perp^{(2)}(q^2) \equiv T_1(q^2) \quad \Rightarrow \mathbf{aT_1} = \mathbf{0}$$

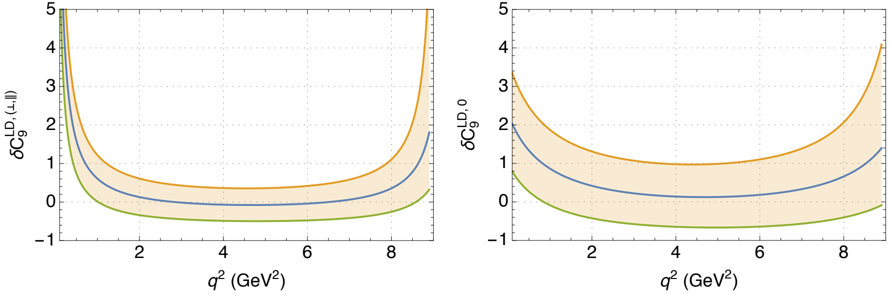
Point also completely missed in CFFMPSV!!

Inspired by Khodjamirian et al (KMPW): $C_9 \to C_9 + s_i\, \delta C_9^{\mathrm{LD}(i)}(q^2)$

Notice that KMPW implies $s_i = 1$, but we vary it independently $s_i = 0 \pm 1$, $i = 0, \perp, \|$ (Zwicky)

$$\delta C_9^{\mathrm{LD},(\perp,\|)}(q^2) = \frac{a^{(\perp,\|)} + b^{(\perp,\|)} q^2 [c^{(\perp,\|)} - q^2]}{b^{(\perp,\|)} q^2 [c^{(\perp,\|)} - q^2]}$$

$$\delta C_9^{\mathrm{LD},0}(q^2) = \frac{a^0 + b^0 [q^2 + s_0][c^0 - q^2]}{b^0 [q^2 + s_0][c^0 - q^2]}$$



Obtaining from fitting the long-distance part to KMPW.

The distribution (massless case) including the **S-wave** and normalized to Γ'_{full}:

$$\frac{1}{\Gamma'_{full}} \frac{d^4\Gamma}{dq^2\, d\cos\theta_K\, d\cos\theta_l\, d\phi} = \frac{9}{32\pi}\Big[\frac{3}{4}\mathbf{F_T}\sin^2\theta_K + \mathbf{F_L}\cos^2\theta_K + (\frac{1}{4}\mathbf{F_T}\sin^2\theta_K - \mathbf{F_L}\cos^2\theta_K)\cos 2\theta_l$$

$$+\sqrt{\mathbf{F_T F_L}}\left(\frac{1}{2}\mathbf{P'_4}\sin 2\theta_K \sin 2\theta_l \cos\phi + \mathbf{P'_5}\sin 2\theta_K \sin\theta_l \cos\phi\right) + 2\mathbf{P_2 F_T}\sin^2\theta_K\cos\theta_l + \frac{1}{2}\mathbf{P_1 F_T}\sin^2\theta_K \sin^2\theta_l \cos 2\phi$$

$$-\sqrt{\mathbf{F_T F_L}}\left(\mathbf{P'_6}\sin 2\theta_K \sin\theta_l \sin\phi - \frac{1}{2}\mathbf{P'_8}\sin 2\theta_K \sin 2\theta_l \sin\phi\right) - \mathbf{P_3 F_T}\sin^2\theta_K \sin^2\theta_l \sin 2\phi\Big](1 - \mathbf{F_S}) + \frac{1}{\Gamma'_{full}}\mathbf{W_S}$$

- in **blue** the set of relevant observables $\mathbf{P_{1,2}}$, $\mathbf{P'_{4,5}}$ that are functions of $A^{L,R}_{\perp,\|,0}$.
- the S-wave terms are (see discussion [M'12] & [HM'15]) not all free observables:

$$\frac{\mathbf{W_S}}{\Gamma'_{full}} = \frac{3}{16\pi}\Big[\mathbf{F_S}\sin^2\theta_\ell + \mathbf{A_S}\sin^2\theta_\ell\cos\theta_K + \mathbf{A_S^4}\sin\theta_K\sin 2\theta_\ell\cos\phi$$

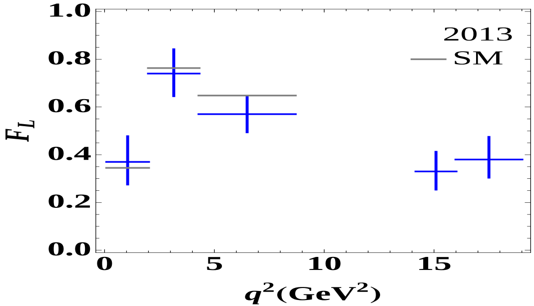
$$+\mathbf{A_S^5}\sin\theta_K\sin\theta_\ell\cos\phi + \mathbf{A_S^7}\sin\theta_K\sin\theta_\ell\sin\phi + \mathbf{A_S^8}\sin\theta_K\sin 2\theta_\ell\sin\phi\Big]$$

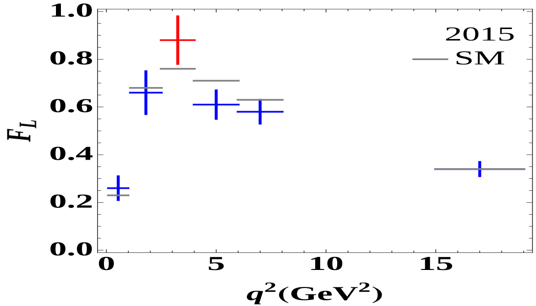
Symmetries tell you that a complete basis (lepton masses to zero) is, for instance:

$\{\Gamma'_{K^*}, F_L, P_1, P_2, P_3, P'_4, P'_5, P'_6\}$ and only 4 of $\{F_S, A_S, A_S^4, A_S^5, A_S^7, A_S^8\}$ are independent.

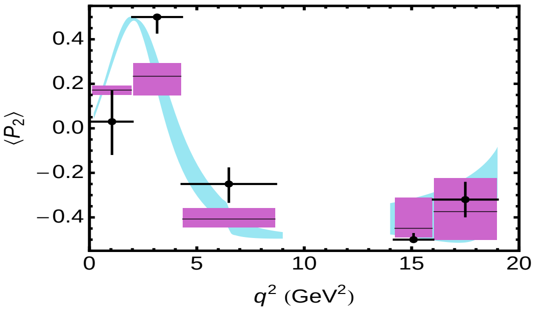
What happened to P_2 in 2015?

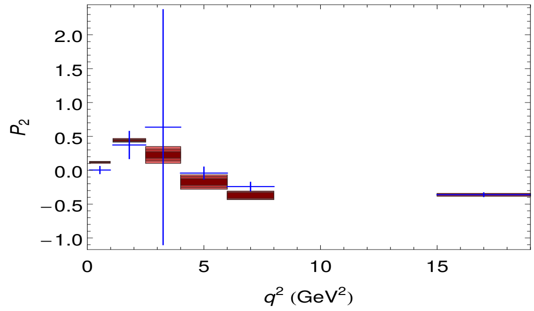
The new binning of F_L in 2015 had a temporary effect on the very interesting bin [2.5,4]





Tiny unfortunate fluctuation up.





$$P_2 \propto \frac{1}{(1 - F_L)}$$

More data (in this bin) is crucial.

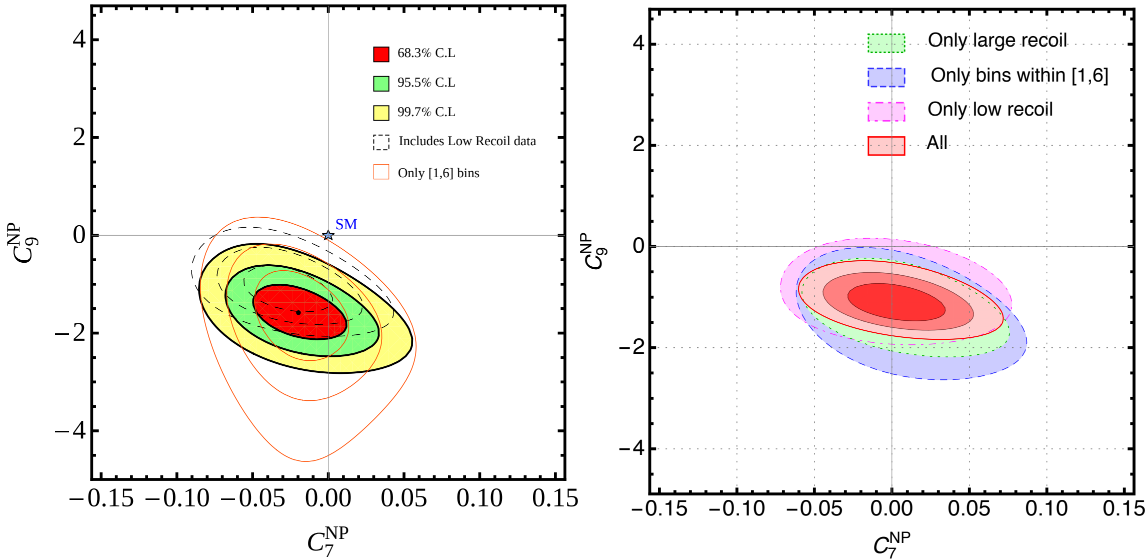


Figure: *For the scenario where NP occurs in the two Wilson coefficients $\mathcal{C}_7$ and $\mathcal{C}_9$, we compare the situation from the analysis in Fig. 1 of Ref. DMV'13(on the left) and the current situation (on the right). On the right, we show the 3 σ regions allowed by large-recoil only (dashed green), by bins in the [1-6] range (long-dashed blue), by low recoil (dot-dashed purple) and by considering all data (red, with 1,2,3 σ contours).*

Bin (0.1,0.98) lepton-mass effect

LHCb naturally given the limited statistics takes the massless lepton limit. They measure:

$$\frac{1}{d(\Gamma+\bar\Gamma)/dq^2}\frac{d^3(\Gamma+\bar\Gamma)}{d\Omega} = \frac{9}{32\pi}\left[\frac{3}{4}(1-F_L^{LHCb})\sin^2\theta_K + F_L^{LHCb}\cos^2\theta_K \right.$$
$$\left. + \frac{1}{4}(1-F_L^{LHCb})\sin^2\theta_K\cos 2\theta_l - F_L^{LHCb}\cos^2\theta_K\cos 2\theta_l + \ldots\right]$$

which is modified once lepton masses are considered

$$\frac{1}{d(\Gamma+\bar\Gamma)/dq^2}\frac{d^3(\Gamma+\bar\Gamma)}{d\Omega} = \frac{9}{32\pi}\left[\frac{3}{4}\hat F_T\sin^2\theta_K + \hat F_L\cos^2\theta_K \right.$$
$$\left. + \frac{1}{4}F_T\sin^2\theta_K\cos 2\theta_l - F_L\cos^2\theta_K\cos 2\theta_l + \ldots\right]$$

where $\hat F_{T,L}$ and $F_{L,T}$ are [**JM'12**]. All our observables are thus written and computed in terms of the longitudinal and transverse polarisation fractions $F_{L,T}$

$$F_L = -\frac{J_{2c}}{d(\Gamma+\bar\Gamma)/dq^2} \qquad F_T = 4\frac{J_{2s}}{d(\Gamma+\bar\Gamma)/dq^2} \qquad \Rightarrow \qquad \hat F_L = \frac{J_{1c}}{d(\Gamma+\bar\Gamma)/dq^2}$$

WHEN measured value $\hat F_L$ is used instead of F_L SM prediction is shifted towards the data in 1st bin

$$\langle F_L\rangle_{[0.1,0.98]} = 0.21 \to 0.26\,, \qquad \langle P_2\rangle_{[0.1,0.98]} = 0.12 \to 0.09\,,$$
$$\langle P_4'\rangle_{[0.1,0.98]} = -0.49 \to -0.38\,, \qquad \langle P_5'\rangle_{[0.1,0.98]} = 0.68 \to 0.53\,.$$

		$\lvert\delta\mathcal{C}_7\rvert = 0.1$	$\lvert\delta\mathcal{C}_9\rvert = 1$	$\lvert\delta\mathcal{C}_{10}\rvert = 1$	$\lvert\delta\mathcal{C}_{7'}\rvert = 0.1$	$\lvert\delta\mathcal{C}_{9'}\rvert = 1$	$\lvert\delta\mathcal{C}_{10'}\rvert = 1$
$\langle P_1\rangle_{[0.1,.98]}$	$+\lvert\delta C_i\rvert$	$--$	$--$	$--$	-0.53	-0.05	$--$
	$-\lvert\delta C_i\rvert$	$--$	$--$	$--$	$+0.52$	$+0.05$	$--$
$\langle P_1\rangle_{[6,8]}$	$+\lvert\delta C_i\rvert$	$--$	$--$	$--$	$+0.11$	$+0.16$	$-\mathbf{0.37}$
	$-\lvert\delta C_i\rvert$	$--$	$--$	$--$	$-\mathbf{0.12}$	$-\mathbf{0.17}$	$+0.37$
$\langle P_1\rangle_{[15,19]}$	$+\lvert\delta C_i\rvert$	$--$	$--$	$--$	$+\mathbf{0.03}$	$+\mathbf{0.15}$	-0.14
	$-\lvert\delta C_i\rvert$	$--$	$--$	$--$	-0.03	-0.11	$+\mathbf{0.19}$
$\langle P_2\rangle_{[2.5,4]}$	$+\lvert\delta C_i\rvert$	-0.31	-0.21	$+\mathbf{0.05}$	$--$	$--$	$--$
	$-\lvert\delta C_i\rvert$	$+\mathbf{0.19}$	$+\mathbf{0.15}$	-0.04	-0.03	$--$	$--$
$\langle P_2\rangle_{[6,8]}$	$+\lvert\delta C_i\rvert$	-0.07	-0.09	-0.06	$--$	$--$	$--$
	$-\lvert\delta C_i\rvert$	$+\mathbf{0.11}$	$+\mathbf{0.17}$	$+\mathbf{0.05}$	$--$	$--$	$--$
$\langle P_2\rangle_{[15,19]}$	$+\lvert\delta C_i\rvert$	$--$	$--$	$--$	$--$	-0.05	$+0.06$
	$-\lvert\delta C_i\rvert$	$--$	$+0.04$	$--$	$--$	$+0.05$	-0.06
$\langle P_4'\rangle_{[6,8]}$	$+\lvert\delta C_i\rvert$	$+\mathbf{0.04}$	$--$	$--$	-0.11	-0.10	$+\mathbf{0.17}$
	$-\lvert\delta C_i\rvert$	-0.05	$--$	$--$	$+\mathbf{0.09}$	$+\mathbf{0.10}$	-0.20
$\langle P_4'\rangle_{[15,19]}$	$+\lvert\delta C_i\rvert$	$--$	$--$	$--$	$--$	$-\mathbf{0.06}$	$+0.05$
	$-\lvert\delta C_i\rvert$	$--$	$--$	$--$	$--$	$+0.04$	$-\mathbf{0.08}$
$\langle P_5'\rangle_{[4,6]}$	$+\lvert\delta C_i\rvert$	-0.11	-0.15	-0.10	-0.11	-0.06	$+\mathbf{0.21}$
	$-\lvert\delta C_i\rvert$	$+\mathbf{0.16}$	$+\mathbf{0.28}$	$+\mathbf{0.09}$	$+\mathbf{0.15}$	$+\mathbf{0.10}$	-0.21
$\langle P_5'\rangle_{[6,8]}$	$+\lvert\delta C_i\rvert$	-0.04	-0.07	-0.07	-0.08	-0.08	$+\mathbf{0.19}$
	$-\lvert\delta C_i\rvert$	$+\mathbf{0.07}$	$+\mathbf{0.19}$	$+\mathbf{0.09}$	$+\mathbf{0.10}$	$+\mathbf{0.11}$	-0.18

$$J_{1s} = \frac{(2+\beta_\ell^2)}{4}\left[|A_\perp^L|^2 + |A_\parallel^L|^2 + (L\to R)\right] + \frac{4m_\ell^2}{q^2}\mathrm{Re}\left(A_\perp^L A_\perp^{R^*} + A_\parallel^L A_\parallel^{R^*}\right),$$

$$J_{1c} = |A_0^L|^2 + |A_0^R|^2 + \frac{4m_\ell^2}{q^2}\left[|A_t|^2 + 2\mathrm{Re}(A_0^L A_0^{R^*})\right] + \beta_\ell^2|A_S|^2,$$

$$J_{2s} = \frac{\beta_\ell^2}{4}\left[|A_\perp^L|^2 + |A_\parallel^L|^2 + (L\to R)\right], \quad J_{2c} = -\beta_\ell^2\left[|A_0^L|^2 + (L\to R)\right],$$

$$J_3 = \frac{1}{2}\beta_\ell^2\left[|A_\perp^L|^2 - |A_\parallel^L|^2 + (L\to R)\right], \quad J_4 = \frac{1}{\sqrt{2}}\beta_\ell^2\left[\mathrm{Re}(A_0^L A_\parallel^{L^*}) + (L\to R)\right],$$

$$J_5 = \sqrt{2}\beta_\ell\left[\mathrm{Re}(A_0^L A_\perp^{L}{}^*) - (L\to R) - \frac{m_\ell}{\sqrt{q^2}}\mathrm{Re}(A_\parallel^L A_S^* + A_\parallel^R A_S^*)\right],$$

$$J_{6s} = 2\beta_\ell\left[\mathrm{Re}(A_\parallel^L A_\perp^{L}{}^*) - (L\to R)\right], \quad J_{6c} = 4\beta_\ell\frac{m_\ell}{\sqrt{q^2}}\mathrm{Re}\left[A_0^L A_S^* + (L\to R)\right],$$

$$J_7 = \sqrt{2}\beta_\ell\left[\mathrm{Im}(A_0^L A_\parallel^{L^*}) - (L\to R) + \frac{m_\ell}{\sqrt{q^2}}\mathrm{Im}(A_\perp^L A_S^* + A_\perp^R A_S^*)\right],$$

$$J_8 = \frac{1}{\sqrt{2}}\beta_\ell^2\left[\mathrm{Im}(A_0^L A_\perp^{L}{}^*) + (L\to R)\right], \quad J_9 = \beta_\ell^2\left[\mathrm{Im}(A_\parallel^{L^*} A_\perp^L) + (L\to R)\right]$$

In red lepton mass terms and $\beta_\ell = \sqrt{1 - 4m_\ell^2/q^2}$

A glimpse into the future: Wilson coefficients versus Anomalies

		R_K	$\langle P_5' \rangle_{[4,6],[6,8]}$	$\mathcal{B}_{B_s\to\phi\mu\mu}$	$\mathcal{B}_{B_s\to\mu\mu}$	best-fit-point of global fit
$\mathcal{C}_9^{NP}$	$+$					
	$-$	✓	✓ [100%]	✓		X
$\mathcal{C}_{10}^{NP}$	$+$	✓	[36%]	✓	✓	X
	$-$		✓ [32%]			
$\mathcal{C}_{9'}$	$+$		[21%]	✓		X
	$-$	✓	✓ [36%]			
$\mathcal{C}_{10'}$	$+$	✓	✓ [75%]			
	$-$		[75%]	✓	✓	X

Table: *A checkmark (✓) indicates that a shift in the Wilson coefficient with this sign moves the prediction in the right direction to solve the corresponding anomaly. $\mathcal{B}_{B_s\to\mu\mu}$ is not an anomaly but a very mild tension.*

- $\mathcal{C}_9^{NP} < 0$ is consistent with all anomalies. This is the reason why it gives a strong pull.
- $\mathcal{C}_{10}^{NP}$, $C'_{9,10}$ fail in some anomaly. BUT
  - $\Rightarrow$ $\mathcal{C}_{10}^{NP}$ is the most promising coefficient after $\mathcal{C}_9$.
  - $\Rightarrow$ C'_9, C'_{10} seems quite inconsistent between the different anomalies and the global fit.

More technical arguments why scheme-2 **is not** an appropriate scheme

In the old scheme used by (also JC'14): $\xi_\perp^{(2)}(\mathbf{q^2}) \equiv \mathbf{T_1}(\mathbf{q^2})$, $\xi_\parallel^{(2)}(\mathbf{q^2}) \equiv \frac{\mathbf{m_{K^*}}}{\mathbf{E}}\mathbf{A_0}(\mathbf{q^2})$.

$\Rightarrow$ Power corrections associated to $\Delta T_1^\Lambda(q^2)$ and $\Delta A_0^\Lambda(q^2)$ are absorbed in $\xi_{\perp,\parallel}$.

Problems of T_1 choice:

- Extracting $T_1(0)$ from data on $B \to K^*\gamma$ is plagued of assumptions (as done in JC'12):
  1) assumption of no NP in $C_7^{(\prime)}$ + ignoring possible non-factorizable power corrections.
- Taking T_1 from LCSR and use it to define $\xi_\perp$ is also **non-optimal** (as done in JC'14).

$$A_\perp^{L,R} = \mathcal{N}_\perp \left[\mathcal{C}^+_{9\pm10} [\mathbf{V}^{\mathbf{sff}+\alpha_\mathbf{s}}(\mathbf{q^2}) + \Delta V^\Lambda] + \mathcal{C}_7^+ [\mathbf{T_1}^{\mathbf{sff}+\alpha_\mathbf{s}}(\mathbf{q^2}) + \Delta T_1^\Lambda] \right] + \mathcal{O}(\alpha_s, \Lambda/m_b, ...)$$

If one is interested in obtaining accurated predictions for observables dominated by C_9 (like P_5') better to have a good control of p.c on V than in T_1.

$\Rightarrow$ T_1 may be a good choice for observables dominated by C_7.

Problem of A_0 choice:

P_i observables do not depend on $A_0(q^2)$ FF. $\Rightarrow$ A_0 choice would be a good choice for lepton-mass suppressed observables.

B-meson distribution amplitudes.

FF-KMPW	$F^i_{BK^{(*)}}(0)$	b^i_1
f^+_{BK}	$0.34^{+0.05}_{-0.02}$	$-2.1^{+0.9}_{-1.6}$
f^0_{BK}	$0.34^{+0.05}_{-0.02}$	$-4.3^{+0.8}_{-0.9}$
f^T_{BK}	$0.39^{+0.05}_{-0.03}$	$-2.2^{+1.0}_{-2.00}$
V^{BK^*}	$\mathbf{0.36^{+0.23}_{-0.12}}$	$-4.8^{+0.8}_{-0.4}$
$A_1^{BK^*}$	$\mathbf{0.25^{+0.16}_{-0.10}}$	$0.34^{+0.86}_{-0.80}$
$A_2^{BK^*}$	$0.23^{+0.19}_{-0.10}$	$-0.85^{+2.88}_{-1.35}$
$A_0^{BK^*}$	$0.29^{+0.10}_{-0.07}$	$-18.2^{+1.3}_{-3.0}$
$T_1^{BK^*}$	$0.31^{+0.18}_{-0.10}$	$-4.6^{+0.81}_{-0.41}$
$T_2^{BK^*}$	$0.31^{+0.18}_{-0.10}$	$-3.2^{+2.1}_{-2.2}$
$T_3^{BK^*}$	$0.22^{+0.17}_{-0.10}$	$-10.3^{+2.5}_{-3.1}$

Table: The $B \to K^{(*)}$ form factors from LCSR and their z-parameterization.

Light-meson distribution amplitudes+EOM.

- Interestingly in BSZ (update from BZ) most relevant FF from BZ moved towards KMPW. For example:

$$V^{BZ}(0) = 0.41 \to 0.37 \quad T_1^{BZ}(0) = 0.33 \to 0.31$$

- The size of uncertainty in *BSZ* = size of error of p.c.

FF-BSZ	$B \to K^*$	$B_s \to \phi$	$B_s \to K^*$
$A_0(0)$	0.391 ± 0.035	0.433 ± 0.035	0.336 ± 0.032
$A_1(0)$	$\mathbf{0.289 \pm 0.027}$	0.315 ± 0.027	0.246 ± 0.023
$A_{12}(0)$	0.281 ± 0.025	0.274 ± 0.022	0.246 ± 0.023
$V(0)$	$\mathbf{0.366 \pm 0.035}$	0.407 ± 0.033	0.311 ± 0.030
$T_1(0)$	0.308 ± 0.031	0.331 ± 0.030	0.254 ± 0.027
$T_2(0)$	0.308 ± 0.031	0.331 ± 0.030	0.254 ± 0.027
$T_{23}(0)$	0.793 ± 0.064	0.763 ± 0.061	0.643 ± 0.058

Table: Values of the form factors at $q^2 = 0$ and their uncertainties.

Helicity Form Factors

All FF determinations are computed in the transversity basis ($A_{\perp,\|,0}$) and correspond to $V, A_{0,1,2}, T_{1,2,3}$.

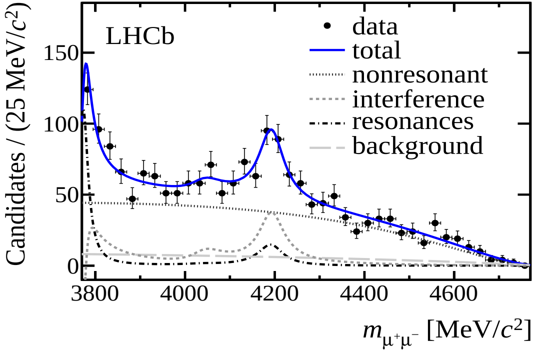
But some people prefer (at their own risk) to use an helicity basis:

$$
\begin{aligned}
V_{\pm}(q^2) &= \frac{1}{2}\left[\left(1+\frac{m_V}{m_B}\right)A_1(q^2) \mp \frac{\lambda^{1/2}}{m_B(m_B+m_V)}V(q^2)\right], \\
V_0(q^2) &= \frac{1}{2m_V\lambda^{1/2}(m_B+m_V)}\left[(m_B+m_V)^2(m_B^2-q^2-m_V^2)A_1(q^2)-\lambda A_2(q^2)\right], \\
T_{\pm}(q^2) &= \frac{m_B^2-m_V^2}{2m_B^2}T_2(q^2) \mp \frac{\lambda^{1/2}}{2m_B^2}T_1(q^2), \\
T_0(q^2) &= \frac{m_B}{2\,m_V\lambda^{1/2}}\left[(m_B^2+3m_V^2-q^2)T_2(q^2)-\frac{\lambda}{(m_B^2-m_V^2)}T_3(q^2)\right], \\
S(q^2) &= A_0(q^2),
\end{aligned}
\tag{31}
$$

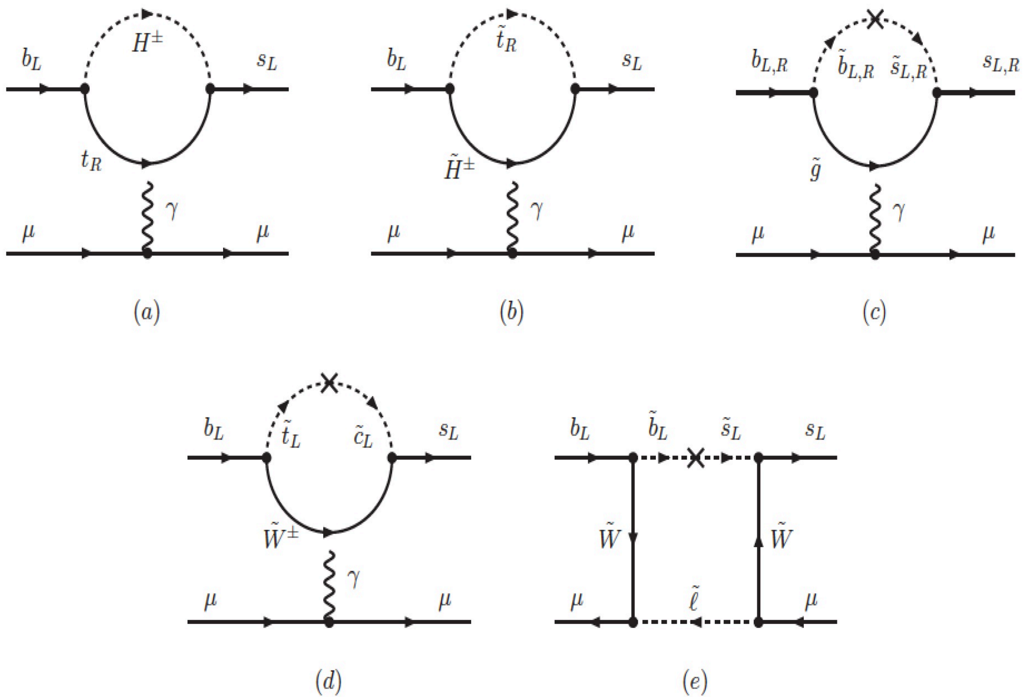
Theoretical description of $B \to K^* \ell^+ \ell^-$ @ large-q^2

- It corresponds to **large** $\sqrt{q^2} \sim \mathcal{O}(m_b)$ above Ψ' mass, i.e., E_K is around GeV or below.
- OPE in $E_K/\sqrt{q^2}$ or $\Lambda_{QCD}/\sqrt{q^2}$ (Buchalla et al). **NLO QCD correct.** to the OPE coeffs (Greub et al)
- **Lattice QCD form factors with correlations** (Horgan et al proceeding update)
- Estimates on BR from GP (5%) and BBF (2%) using Shifman's model.
  $\Rightarrow \pm 10\%$ on angular observables to account for possible Duality Violations.

Existence of $c\bar{c}$ **resonances** in this region (clearly seen $\psi(4160)$ in $B^- \to K^- \mu^+ \mu^-$),
$\Rightarrow$ require to take a long bin.



... but this region is neither the most sensitive to New Physics nor where interesting things happen!



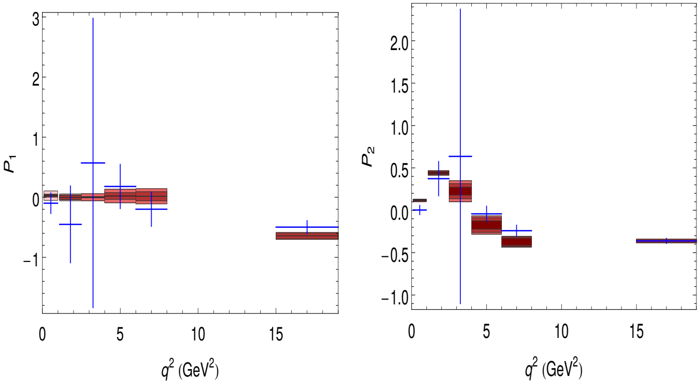
b_L
$H^\pm$
s_L
t_R
γ
μ
μ
(a)
b_L
$\tilde{t}_R$
s_L
$\tilde{H}^\pm$
γ
μ
μ
(b)
$b_{L,R}$
$\tilde{b}_{L,R}$
$\tilde{s}_{L,R}$
$s_{L,R}$
$\tilde{g}$
γ
μ
μ
(c)
b_L
$\tilde{t}_L$
$\tilde{c}_L$
s_L
$\tilde{W}^\pm$
γ
μ
μ
(d)
b_L
$\tilde{b}_L$
$\tilde{s}_L$
s_L
$\tilde{W}$
$\tilde{W}$
μ
$\tilde{\ell}$
μ
(e)

A few properties of the relevant FFI observables $P_{1,2}$ (driving the ambulance)

The idea of **exact cancellation of the poorly known soft form factors at LO** at the zero of A_{FB} was incorporated in the construction of the P_i (this is why they are "**clean**" compared to the S_i)

P_1 and P_2 observables function of $A_\perp$ and $A_{||}$ amplitudes

- **P_1**: Proportional to $|A_\perp|^2 - |A_{||}|^2$
  - Test the LH structure of SM.
    The existence of RH currents breaks the SM relation $A_\perp \sim -A_{||}$
- **P_2**: Proportional to $\mathrm{Re}(A_i A_j)$
  - Zero of P_2 at the same position as the zero of A_{FB}
  - P_2 is the clean version of A_{FB}. Their different normalizations offer different sensitivities.



- P_3 and $P'_{6,8}$ are proportional to $\mathrm{Im} A_i A_j$ and small if there are no large phases. All are < 0.1.
- P_i^{CP} are all negligibly small if there is no New Physics in weak phases.