Low q^2 $b \to sll$ and interplay with radiative

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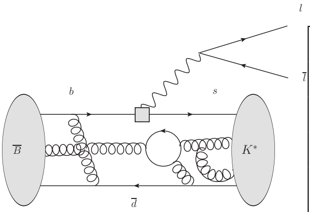
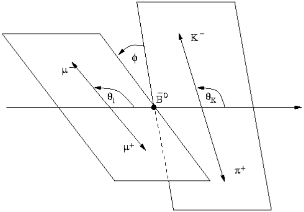
Implications of LHCb measurements and future prospects
Oct. 15-17th, 2014

$\bar{B} \to \bar{K}^* \ell^+ \ell^-$

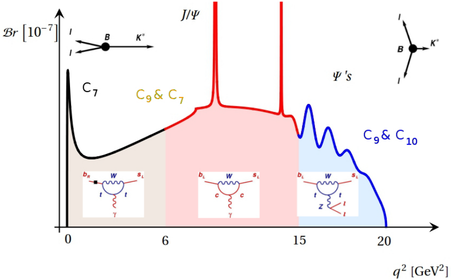


Expt.	∼# events
CDF	100 PRL106(2011)161801
BaBar	150 PRD86(2012)032012
Belle	200 PRL103(2009)171801
CMS	400 PLB727(2013)77
ATLAS	500 arXiv:1310.4213
LHCb (μ)	1000 (1 fb^{-1}) JHEP 1308 (2013) 131
LHCb (e)	128 ([0.0004, 1] GeV^2) M Borsato (LHCb)

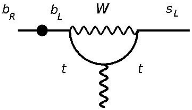
- **4-body decay**



$$\frac{d^{(4)}\Gamma}{dq^2\, d(\cos\theta_l) d(\cos\theta_k) d\phi} = \frac{9}{32\pi}\Big(I_1^s \sin^2\theta_k + I_1^c \cos^2\theta_k$$
$$+ \quad (I_2^s \sin^2\theta_k + I_2^c \cos^2\theta_k)\cos 2\theta_l + I_3 \sin^2\theta_k \sin^2\theta_l \cos 2\phi$$
$$+ \quad I_4 \sin 2\theta_k \sin 2\theta_l \cos\phi + I_5 \sin 2\theta_k \sin\theta_l \cos\phi + I_6 \sin^2\theta_k \cos\theta_l$$
$$+ \quad I_7 \sin 2\theta_k \sin\theta_l \sin\phi + I_8 \sin 2\theta_k \sin 2\theta_l \sin\phi + I_9 \sin^2\theta_k \sin^2\theta_l \sin 2\phi\Big)$$



- SM $\bar{B} \to \bar{K}^* \gamma$ mostly produces left-handed photons!



$$\mathcal{O}_7 = \frac{e}{4\pi^2}\, \hat{m}_b\, \bar{s}\sigma_{\mu\nu}\, P_R\, b\, F^{\mu\nu}$$

Chirally-flipped operators

$$\mathcal{O}_7' = \frac{e}{4\pi^2}\, \hat{m}_b\, \bar{s}\sigma_{\mu\nu} P_L b\, F^{\mu\nu}$$

Connecting theory to experiment: The helicity amplitudes

- Helicity amplitudes $\lambda = \pm 1, 0$

$$H_V(\lambda) = -iN\Big\{C_9\,\tilde{V}_{L\lambda} - \frac{m_B^2}{q^2}\Big[\frac{2\,\hat{m}_b}{m_B}C_{7\gamma}\,\tilde{T}_{L\lambda} - 16\pi^2 h_\lambda\Big]\Big\},$$

$$H_A(\lambda) = -iNC_{10}\,\tilde{V}_{L\lambda}, \qquad H_P = iN\frac{2\,m_l\hat{m}_b}{q^2}C_{10}\Big(\tilde{S}_L + \frac{m_s}{m_b}\tilde{S}_R\Big)$$

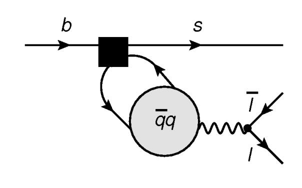
C_9 is exposed to various hadronic backgrounds

- Hadronic form factors

  Helicity basis: Best suited for the analysis of power corrections

  Bharucha it et al.JHEP 1009 (2010) 090, Jäeger and JMC JHEP1305(2013)043

- Non-local contribution



$$h_\lambda \propto \int d^4y e^{iq\cdot y}\langle \bar{K}^*|j^{\mathrm{em,had},\mu}(y)\mathcal{H}^{\mathrm{had}}(0)|\bar{B}\rangle\epsilon_\mu^*$$

Especially sensitive to $c\bar{c}$ contributions!

Form Factors at large recoil

- **Heavy-quark** and **large-recoil** (K^*) limit only **2** independent "soft form factors"

$$T_+ = V_+ = 0, \qquad T_- = V_- = \frac{2E}{m_B}\xi_\perp, \qquad T_0 = V_0 = S = \frac{E}{m_{K^*}}\xi_\|$$

Dugan *et al.* PLB255(1991)583, Charles *et al.* PRD60(1999)014001

- The observable P_5' Matias *et al.*'12

$$P_5' = \frac{I_5}{2\sqrt{-I_{2s}I_{2c}}} = \frac{\mathrm{Re}[(H_V^- - H_V^+)H_A^{0*} + (H_A^- - H_A^+)H_V^{0*}]}{\sqrt{(|H_V^0|^2 + |H_A^0|^2)(|H_V^+|^2 + |H_V^-|^2 + |H_A^+|^2 + |H_A^-|^2)}}$$

- *Rationale* behind P' basis: Ignore in first app. α_s corrections and h_λ

$$H_V^0 \propto \xi_\|, \qquad H_V^- \propto \xi_\perp, \qquad H_V^+ \sim 0$$

$$P_5' \simeq \frac{C_{10}\left(C_{9,\perp} + C_{9,\|}\right)}{\sqrt{(C_{9,\|}^2 + C_{10}^2)(C_{9,\perp}^2 + C_{10}^2)}}, \qquad \begin{cases} C_{9,\perp} = C_9^{\rm eff}(q^2) + \frac{2\, m_b\, m_B}{q^2}\, C_7^{\rm eff} \\ C_{9,\|} = C_9^{\rm eff}(q^2) + \frac{2\, m_b\, E}{q^2}\, C_7^{\rm eff} \end{cases}$$

P_5' "hadronic independent" at $\mathcal{O}(\alpha_s^0, (\frac{\Lambda}{E})^0)$

- α_s corrections can be computed to any order in QCDf or SCET

Beneke *et al.* NPB592(2001)3, NPB612(2001)25, NPB685(2004)249, Bauer *et al.* PRD63(2001)114020

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$P_i^{(\prime)}$ are sensitive to power-corrections!

- Model-independent parameterization (10% p.c.'s)
- Constrained by **exact relations** or **experimental data**

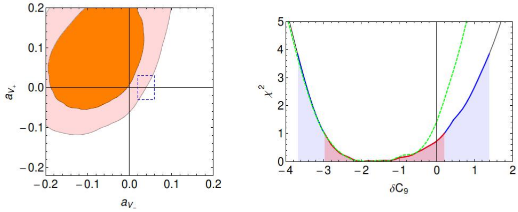
The significance of the P_5' anomaly

LHCb PRL'13, Descotes-Genon *et al.*'13, Altmannshofer *et al.*...

- The anomaly could be *partly* accommodated in the SM with p.c.'s

$$H_V^- \sim \left\{ C_9 (V_-^{\rm QCDf} + a_{V_-}) - \frac{m_B^2}{q^2}\left[\frac{2\,\hat{m}_b}{m_B} C_{7\gamma}\, T_-^{\rm QCD} - 16\pi^2 h_-\right]\right\}$$

- We fit all the P_i' observables in the bin [1,6] GeV^2 using the "*R*-**Fit method**" Profile likelihood over QCD parameters PRELIMINARY Jäger and JMC, to appear



- Similar conclusions were drawn from a bayesian analysis

  Beaujean *et al.* arXiv:1310.2478,JHEP1208(2012)030

  - Sizable power corrections (scale-factor method)

- LCSR form factor results (Ball *et al.*'05) suggest values for p.c. parameters that imply a higher significance (blue box)

P_1 and P_3^{CP} and sensitivity to C_7'

- At very low q^2 amplitude dominated by $H_V(\pm)$ (photon pole)

$$H_V(\pm) \simeq iN\frac{2\, m_b\, m_B}{q^2}\left(C_{7\gamma}\, T_\pm - C'_{7\gamma}\, T_\mp\right) - 16\pi^2 h_\pm$$

- $H^+_{A,V}$ suppressed at factorisable level Burdman *et al.*'01

  - **Exact relation:** $T_+(0) = 0 \Longrightarrow T_+(q^2) \sim \mathcal{O}(\Lambda/E) \times q^2/m_b^2$
  - **Helicity hierarchy:** Contributions to h_+ are $(\Lambda/m_B)^2$ Jäger and JMC'12

- Super-clean observables:

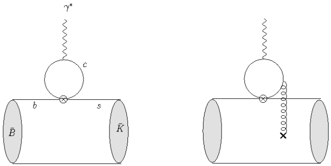
$$P_1 \equiv A_T^{(2)} = 2\,\frac{I_3 + \bar{I}_3}{\Gamma_T}, \qquad P_3^{\rm CP} = -2\,\frac{I_9 - \bar{I}_9}{\Gamma_T}$$

$$I_3 = \frac{-2\,{\rm Re}(H_V^+ H_V^{-\,*} + H_A^+ H_A^{-\,*})}{|H_V^+|^2 + |H_V^-|^2 + |H_A^+|^2 + |H_A^-|^2} \simeq \frac{2{\rm Re}(C_7\, C_7')}{|C_7|^2 + |C_7'|^2} \qquad I_9 \simeq \frac{2{\rm Im}(C_7\, C_7')}{|C_7|^2 + |C_7'|^2}$$

  - Null tests of the SM with very good accuracy at very low q^2 Jäger and JMC'12
  - Sensitive to right-handed currents BSM Melikhov *et al.*'98, Kruger *et al.*'05, Becirevic *et al.*'11

- Only the *CP*-combinations $I_9 - \bar{I}_9$ and $I_3 + \bar{I}_3$ are sensitive to New Physics! **Measure P_3^{CP}!!**

Double power suppression of h_+ at low q^2



- **QCDF**: Can be computed at leading-power perturbatively in α_s
  One finds $h_{+|c\bar{c},\mathrm{QCDSF}} = 0$. At subleading powers factorization breaks down
- Long-distance in **light-cone OPE + SRs**: As large as $\Lambda/m_b \sim 10\%$ Khodjamirian *et al.*'10
- Detailed investigation shows $h_{+|c\bar{c},\mathrm{LD}} \sim \mathcal{O}(\frac{\Lambda}{m_b})\, h_{-|c\bar{c},\mathrm{LD}}$!! Jäger and JMC'12
- Power corrections from light quarks double-CKM suppressed but "resonate"
  - **Binned contribution** is very small Jäger and JMC'12
  - **Helicity suppression:** $h_{+|\mathrm{lq},\mathrm{LD}} \sim \mathcal{O}(\Lambda/m_B)^2$ Kagan '04
- Contributions of $\mathcal{O}_8$ to h_λ estimated to be very small Dimou *et al.*'12, Khodjamirian '12

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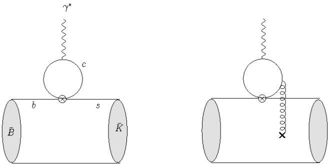

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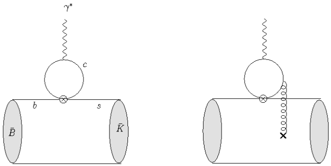

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The electronic mode

- The electronic modes have the end-point very close to $q^2 = 0$
  - Theoretically cleaner: Boosted *BR* at low q^2

$$BR^{e}_{[0.0004,\,1]} = 31^{+15}_{-11}\,10^{-8}, \qquad BR^{\mu}_{[0.1,\,0.98]} = 9.5^{+5.2}_{-3.5}\,10^{-8}$$

  - Enhanced sensitivity to $C_7^{(\prime)}$
- **Experimentally?** $m_\ell = 0$ is a very good approximation
- Predictions for the electronic mode:

F_L	P_1	P_2	P_3^{CP} $[10^{-4}]$
$0.07^{+0.09}_{-0.04}$	$0.030^{+0.045}_{-0.041}$	$-0.054^{+0.015}_{-0.012}$	$0.1^{+0.7}_{-0.6}$

P_4'	P_5'	P_6'	P_8'
$0.18^{+0.06}_{-0.07}$	$0.52^{+0.10}_{-0.11}$	$0.05^{+0.07}_{-0.06}$	$0.01^{+0.08}_{-0.08}$

PRELIMINARY Jäger and JMC, to appear

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  - Enhanced sensitivity to $C_7^{(\prime)}$
- **Experimentally?** $m_\ell = 0$ is a very good approximation
- Errors in P_1 and P_3^{CP} will be statistically dominated!

	QCDF	Fact. p.c.'s	Non-fact. p.c.'s
P_1	0.008	0.009	0.028
P_3^{CP} $[10^{-4}]$	0.3	0.1	0.3

PRELIMINARY Jäger and JMC, to appear

Interplay with the radiative decays

- The radiative modes are sensitive to C_7'

E. Kou, previous talk

$$\mathcal{A}(\bar{B}\to V(\lambda)\gamma(\lambda)) = \lim_{q^2\to 0}\frac{q^2}{e}H_V(q^2=0;\lambda)$$
$$= \frac{iNm_B^2}{e}\left[\frac{2\hat{m}_b}{m_B}(C_{7\gamma}T_\lambda(0) - C_{7\gamma}'T_{-\lambda})(0) - 16\pi^2 h_\lambda(q^2=0)\right]$$

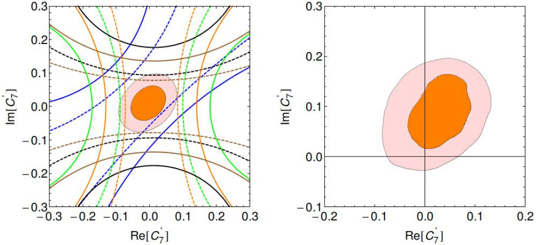
- BR depends on a form factor $T_1(0)$
- BR has real photons in final state: Sensitivity goes as $|C_{7\gamma}'|^2$ (also with $B\to X_s\gamma$)
- **Interference and clean observable:** Time-dependent CP asymmetries

$$S_{K^*\gamma} = \frac{2\,\mathrm{Im}\left[e^{-2\,i\,\beta}\left(H_V^-\,(\bar{H}_V^-)^* + H_V^+\,(\bar{H}_V^+)^*\right)\right]}{|H_V^+|^2+|H_V^-|^2+|\bar{H}_V^+|^2+|\bar{H}_V^-|^2}$$

Atwood *et al.* '97, Ball *et al.* '06

- We predict $S_{K^*\gamma} = -0.02^{+0.016}_{-0.023}\,10^{-2}$ Jäger and JMC, to appear while $S^{\mathrm{HFAG}}_{K^*\gamma} = -0.16\pm 0.22$

Prospects and current bounds on C_7'



PRELIMINARY Jäger and JMC, to appear

$$S \simeq \frac{2\mathrm{Im}(e^{-2i\beta} C_7 C_7')}{|C_7|^2 + |C_7'|^2}, \qquad P_1 \simeq \frac{2\mathrm{Re}(C_7 C_7')}{|C_7|^2 + |C_7'|^2}, \qquad P_3^{\mathrm{CP}} \simeq \frac{2\mathrm{Im}(C_7 C_7')}{|C_7|^2 + |C_7'|^2}$$

- **Left:** Ideal plot assuming $\sigma_{P_i} = 0.25$ for μ and e modes (1 and 2σ)
- **Right:** Profile likelihood to current data (slight tension driven by A_9^{μ}!)
- $B \to K * \{mumu, ee\}$ provide excellent theoretically clean window on C_7'
- With radiative they form a complete system to determine C_7 and C_7'

Conclusions

- **Current status**
- Observables in the semileptonic decays generally exhibit a sensitivity to Λ/m_b

At low q^2 P_1 and P_3^{CP} provide (theoretical) sensitivity to C_7' as small as $\mathcal{O}(\Lambda/m_b)^2 \sim 0.01$

Implications: $B \to K^* \ell\ell$ and radiative decays provide a complete set of clean observables to constrain C_7 and C_7'

Jäger and JMC, to appear

- **Future and prospects**
- New e and μ data eagerly waited for:
  Frequentist approach including QCD parameters in R-fit scheme
  - Improved bounds in the $C_7^{(\prime)}$ planes
  - Finer binning could allow to overconstrain parameter space (WCs+QCD)
  - Assessment of the possible low q^2 anomalies

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Obtention of error bands and comparison

- A standard method for modelling power corrections

  Egede *et al.* JHEP 1010 (2010) 056

  Introduce a scale factor ζ_i per amplitude, e.g.

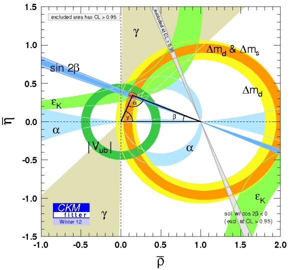
$$H_V(\lambda) \mapsto \zeta_{i,\lambda}\left\{C_9\,\tilde{V}_{L\lambda} - \frac{m_B^2}{q^2}\left[\frac{2\,\hat{m}_b}{m_B}C_{7\gamma}\,\tilde{T}_{L\lambda} - 16\pi^2 h_\lambda\right]\right\}$$

- Run a Montecarlo over ζ_i and other uncertainties and quote 67% interval (th. 1-σ)
- Add $\sigma_{\rm th}$ and $\sigma_{\rm expt}$ in quadratures and perform conventional χ^2 analysis

Two possible issues

1. ζ_i can miss interference between power corrections in FFs or h_λ
2. Is the treatment of theoretical error as experimental adequate?

Obtention of error bands and comparison



We use the *R*fit method

Method employed by **CKMfitter** for treating hadronic uncertainties

Höcker *et al.* EPJC21(2001)225

$$\chi^2(\vec{y}_{\rm ew},\vec{y}_{\rm QCD}) = \left(\frac{x_{{\rm exp},i} - x_{{\rm th},i}(\vec{y}_{\rm ew},\vec{y}_{\rm QCD})}{\sigma_{\rm exp}}\right)^2, \quad \text{if} \quad y_{QCD,i} \in [\bar{y}_i - \sigma_i, \bar{y}_i + \sigma_i] \quad \forall i$$

$$\chi^2(\vec{y}_{\rm ew},\vec{y}_{\rm QCD}) = \infty, \quad \text{otherwise}$$

- Minimize χ^2 scanning $\vec{y}_{\rm QCD}$ by Montecarlo using flat PDFs
- **Our error intervals:** maximum spread of results resulting from Montecarlos

Form factors and PCs

$$F(q^2) \quad = \quad F^\infty(q^2) + a_F + b_F q^2/m_B^2 + \mathcal{O}([q^2/m_B^2]^2). \tag{1}$$

Reference form factors (V_0 and V_- could be used in their stead):

$$\xi_\perp(q^2) \equiv T_1(q^2) \simeq \frac{m_B}{2E} T_-(q^2), \qquad \xi_\parallel(q^2) \equiv S(q^2),$$

$$\xi_\perp(0) = T_-(0) = 0.31(4), \qquad \xi_\parallel(0) = 0.31(6),$$

Modified HQ/LE scalings:

$$\xi_X(q^2) = \xi_X(0) \left(\frac{1}{1 - q^2/m_B^2} \right)^{2+\alpha_X}, \qquad X = \perp, \parallel .$$

$$|\alpha_\perp^{\max}| = 0.2, \qquad |\alpha_\parallel^{\max}| = 0.7.$$

Model independent constraints:

$$a_{T_+} = 0, \qquad a_{V_0} = a_S.$$

$a_{T_-} = a_S = 0$ and $b_{T_-} = b_S = 0$ effectively absorbed in $\xi_{\perp,\parallel}(0)$ and $\alpha_{\perp,\parallel}$

Form factors and PCs (cont ...)

Power corrections estimated bt power counting $\Lambda/m_b \sim 10\%$

$$|a_F^{\text{max,pc}}| \simeq 0.03, \qquad |b_F^{\text{max,pc}}| \simeq 0.10.$$

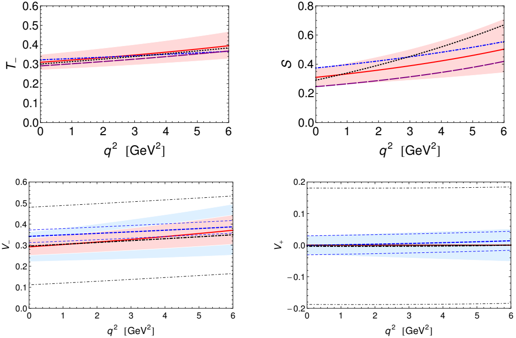


Table : Results for the bin [1, 6] GeV^2 in the SM for a selection of observables and using different schemes for the estimation of the theoretical uncertainties.In the last column we show the experimental data.

	Max. Spread	Max. spread (V_- and V_0)	1σ gaussian	Expt.
P_1	$-0.02^{+0.21}_{-0.23}$	$-0.02^{+0.20}_{-0.21}$	$-0.02^{+0.11}_{-0.11}$	0.15(0.4)
P_2	$-0.20^{+0.44}_{-0.35}$	$-0.19^{+0.37}_{-0.32}$	$-0.18^{+0.19}_{-0.18}$	$-0.66(23)$
P_5'	$-0.27^{+0.48}_{-0.38}$	$-0.28^{+0.38}_{-0.36}$	$-0.27^{+0.20}_{-0.18}$	0.21(21)