# $B \to K^* \ell^+ \ell^-$: Theory, QCD and new physics

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June 19, 2014

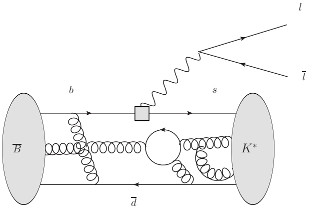
Jäger and JMC JHEP 1305 (2013) 043 and work in progress

MARIE CURIE ACTIONS

European Commission

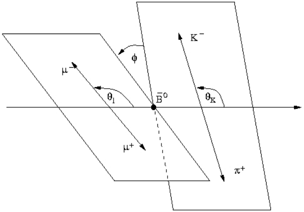
# OUTLINE

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




- **4-body decay**

| 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 | 1000 (1 fb$^{-1}$) JHEP 1308 (2013) 131 |




$$\frac{d^{(4)}\Gamma}{dq^2\, d(\cos\theta_l) d(\cos\theta_k) d\phi} = \frac{9}{32\pi} \Big( I_1^s \sin^2\theta_k + I_1^c \cos^2\theta_k$$

$$+ \quad (I_2^s \sin^2\theta_k + I_2^c \cos^2\theta_k) \cos 2\theta_l + I_3 \sin^2\theta_k \sin^2\theta_l \cos 2\phi$$

$$+ \quad I_4 \sin 2\theta_k \sin 2\theta_l \cos\phi + I_5 \sin 2\theta_k \sin\theta_l \cos\phi + I_6 \sin^2\theta_k \cos\theta_l$$

$$+ \quad I_7 \sin 2\theta_k \sin\theta_l \sin\phi + I_8 \sin 2\theta_k \sin 2\theta_l \sin\phi + I_9 \sin^2\theta_k \sin^2\theta_l \sin 2\phi \Big)$$

Up to $I_i(q^2)$ **12** $q^2$-dependent observables

# The weak Hamiltonian for $b \to s$ transitions

- In the SM we have

$$\mathcal{H}_W = \frac{G_F}{\sqrt{2}} \sum_{p=u,\,c} \lambda_p \left[ C_1 \mathcal{O}_1^p + C_2 \mathcal{O}_2^p + \sum_{i=3,\,10} C_i \mathcal{O}_i \right] ,$$

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

$$\mathcal{O}_1^c = (\bar{c}b)_{V-A}(\bar{s}c)_{V-A} \, , \qquad \mathcal{O}_2^c = (\bar{c}_i b_j)_{V-A}(\bar{s}_j c_i)_{V-A} \, ,$$

$$\mathcal{O}_9 = \frac{\alpha_{\rm em}}{2\pi} (\bar{s}b)_{V-A}(\bar{l}l)_V \, , \qquad \mathcal{O}_{10} = \frac{\alpha_{\rm em}}{2\pi} (\bar{s}b)_{V-A}(\bar{l}l)_A$$

Buchalla *el al.*Rev.Mod.Phys.68(1996)1125

- **Info from DOFs at $\Lambda \sim \mathcal{O}(m_W)$ stored in the Wilson coeffs. $C_i(\mu)$'s**

Table : Wilson coefficients of the SM at $\mu = 4.8$ GeV.

| $C_1$ | $C_2$ | $C_7^{\rm eff}$ | $C_9$ | $C_{10}$ |
|---|---|---|---|---|
| -0.144 | 1.060 | -0.305 | 4.24 | -4.312 |

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- **Info from DOFs at $\Lambda \sim \mathcal{O}(m_W)$ stored in the Wilson coeffs. $C_i(\mu)$'s**
- Physics BSM manifest at the operator level through...
  - Different values of the Wilson coefficients $C_i^{\rm expt.} = C_i^{\rm SM} + \delta C_i$
  - New operators absent or very suppressed in the SM

**Chirally-flipped operators**

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

# A “clean” set of observables

- One can use ratios of $I_i's$ to reduce theoretical uncertainties

  Kruger *et al.* PRD71(2005)094009

- The $P$-basis is composed by the combinations

  Descotes-Genon *et al.*JHEP1301(2013)048

$$P_1 = \frac{I_3}{2I_{2s}}, \qquad P_2 = \frac{I_6}{8I_{2s}}, \qquad P_3 = -\frac{I_9}{4I_{2s}},$$

$$P_4' = \frac{I_4}{\sqrt{-I_{2s}I_{2c}}}, \qquad P_5' = \frac{I_5}{2\sqrt{-I_{2s}I_{2c}}}, \qquad P_6' = -\frac{I_7}{2\sqrt{-I_{2s}I_{2c}}}.$$

plus

$$\Gamma' = \frac{d\Gamma + d\bar{\Gamma}}{dq^2} = \frac{1}{4}\left((3I_{1c} - I_{2c}) + 2\,(3I_{1s} - I_{2s})\right)$$

$$F_L = \frac{3I_{1c} - I_{2c}}{4\Gamma'},$$

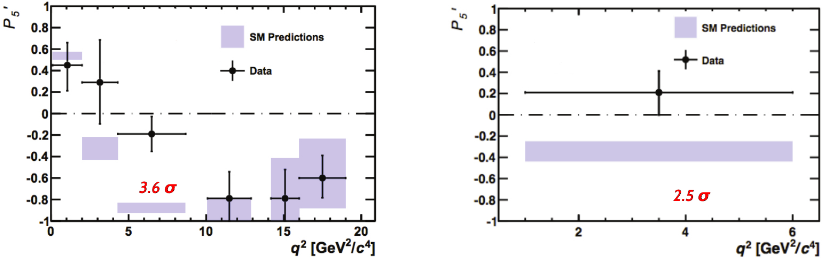
- They are defined such that “leading hadronic uncertainties” factor out

# The $P_5'$ anomaly at low $q^2$ (1 $\text{fb}^{-1}$)

PRL **111,** 191801 (2013) PHYSICAL REVIEW LETTERS week ending 8 NOVEMBER 2013

**Measurement of Form-Factor-Independent Observables in the Decay $B^0 \to K^{*0}\mu^+\mu^-$**

R. Aaij *et al.**
(LHCb Collaboration)
(Received 9 August 2013; published 4 November 2013)



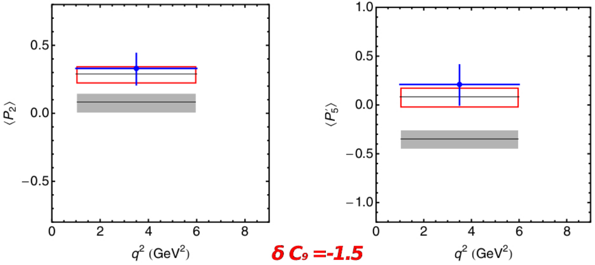

SM predictions from Egede *et al.* JHEP11(2008)032

**There are 2 more fb$^{-1}$ on tape!!**

# The $P_5'$ anomaly: New Physics?

- It was noted that there is another tension in $P_2$ at low $q^2$
- The discrepancies can be solved by a sizable NPs contribution to $C_9$

Descotes-Genon *et al.* PRD88,074002,hep-ph 1311.3876



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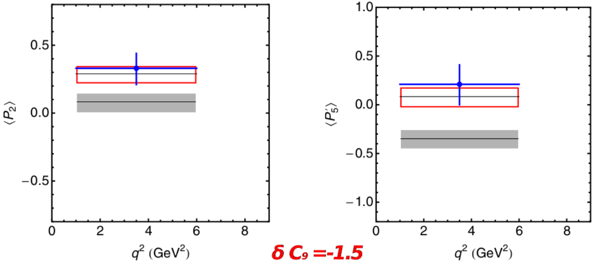



- An independent analysis

  Altmannshofer *et al.* Eur.Phys.J. C73 (2013) 2646

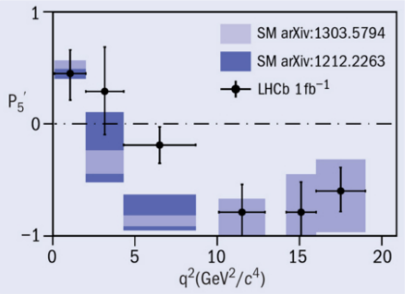
  1. Confirmed the important role of $C_9$ to explain the anomaly
  2. High $q^2$ analysis played an important role in revealing other sources of NPs

# The $P_5'$ anomaly: New Physics?

**CERN COURIER**

Nov 20, 2013

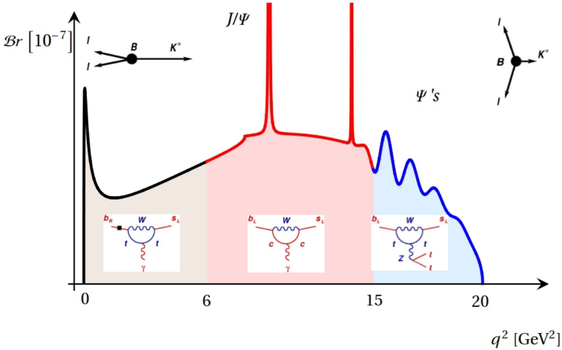
## LHCb and theorists chart a course for discovery




Jäger and JMC, JHEP 1305 (2013) 043

- Larger SM uncertainties in the predictions

**GOAL:** Explain the anomalies largely by *uncertain* hadronic effects?




- **Large-recoil region** (low $q^2$)
  - Heavy to collinear light quark $\Rightarrow$ QCDf or SCET (power-corrections)
  - Dominant effect of the photon pole
- **Charmonium region**
  - Dominated by long-distance (hadronic) effects
  - Starting at the perturbative $c\bar{c}$ threshold $q^2 \simeq 6 - 7$ GeV$^2$
- **Low-recoil region** (high $q^2$)
  - Heavy quark EFT + Operator Product Expansion (OPE) (duality violation)
  - Dominated by semileptonic operators

# Connecting the theory to experiment: The helicity amplitudes

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

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

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

## $C_9$ is exposed to various hadronic backgrounds

- Hadronic form factors

$$-im_B \tilde{V}_{L(R)\lambda}(q^2) = \langle M(\lambda)|\bar{s}\not{\epsilon}^*(\lambda) P_{L(R)} b|\bar{B}\rangle,$$
$$m_B^2 \tilde{T}_{L(R)\lambda}(q^2) = \epsilon^{*\mu}(\lambda) q^\nu \langle M(\lambda)|\bar{s}\sigma_{\mu\nu} P_{R(L)} b|\bar{B}\rangle,$$
$$im_B \tilde{S}_{L(R)}(q^2) = \langle M(\lambda = 0)|\bar{s} P_{R(L)} b|\bar{B}\rangle.$$

- Form factors in the helicity basis

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

# Connecting the theory to experiment: The helicity amplitudes

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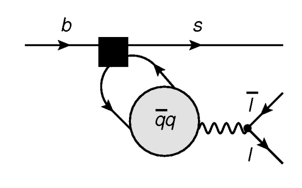
$$H_A(\lambda) = -iNC_{10}\,\tilde{V}_{L\lambda}, \qquad H_P = iN\frac{2\,m_l\hat{m}_b}{q^2}C_{10}\Big(\tilde{S}_L + \frac{m_s}{m_b}\tilde{S}_R\Big)$$

## $C_9$ is exposed to various hadronic backgrounds

- 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"

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

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

- The observable $P_5'$

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

- *Rationale* behind $P'$ basis: Ignore in first app. $\alpha_s$ corrections and $h_\lambda$

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

$$P_5' \simeq \frac{2E^2}{m_B m_{K^*}} F(q^2, C_{7,\gamma}, C_9, C_{10})$$

$F(q^2, C_{7,\gamma}, C_9, C_{10})$ hadronic independent at $\mathcal{O}(\alpha_s^0, (\frac{\Lambda}{E})^0)$

$\alpha_s$ corrections can be computed to any order in QCDf or SCET

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

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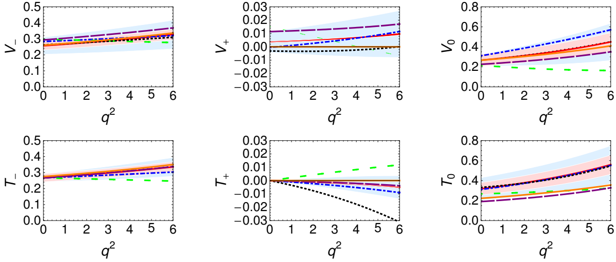
# Agnostic approach to power corrections ($\frac{\Lambda}{E}$)

- We fix $\xi_{\parallel}(0)$ using theoretical predictions

$$\xi_{\perp}(0) = T_1(0) = 0.30(1), \qquad \xi_{\parallel}(0) = \frac{2m_{K^*}}{m_B} A_0(0) = 0.09(2)$$

- Parametrize

$$F^{\mathrm{p.c.},\pm} = \pm a_F \pm b_F \frac{q^2}{m_B^2}$$




- **Light-cone SRs** (Ball&Zwicky'05, Khodjamirian *et al.*'10)
- **QCD SRs** (Colangelo *et al.*'96)
- **Dyson-Schwinger** (Ivanov *et al.*'07)

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| | $V_-$ | $V_+$ | $T_-$ | $T_+$ | $V_0$ | $T_0$ |
|---|---|---|---|---|---|---|
| $\lvert a\rvert_{\rm max}$ | 0.027 | 0.008 | 0 | 0 | 0 | 0.050 |
| $\lvert b\rvert_{\rm max}$ | 0.136 | 0.042 | 0.125 | 0.043 | 0.434 | 0.206 |

**Consistent with power counting**

Power corrections typically at 5% – 20% level

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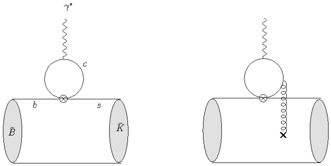
**Power corrections suppressed by $q^2/m_b^2$**

**Exact relations:** $V_0(0) = 0,\ T_+(0) = 0$

# Calculation of $h_\lambda$ at low $q^2$

- **QCDf**: Can be computed at leading-power $\Lambda/E$ perturbatively in $\alpha_s$
- Power corrections from charm-loop weighted by large WCs




- Estimate of the effects obtained using non-local **LCSRs**
  **One can only trust up to 4-6 GeV$^2$!!**

  Khodjamirian *et al.*JHEP1009(2010)089

- Power corrections from light quarks CKM suppressed but “resonate”

$$a_\mu^{\mathrm{had,\,l-q}} \approx \int d^4x\, e^{-iq\cdot x} \sum_{P,P'} \langle 0|j_\mu^{\mathrm{em,\,l-q}}(x)|P'\rangle\langle P'(x)|P(0)\rangle\langle K^* P|\, H_W^{\mathrm{had}}(0)|B\rangle$$

Non-factorizable contributions to $h_+$ are $\Lambda/m_B$ (Jäger and JMC'12)

# Obtention of error bands and comparison

- A standard method for modelling power corrections

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

  Introduce a scale factor $\zeta_i$ per amplitude, e.g.

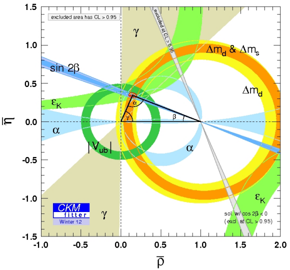
$$H_V(\lambda) \mapsto \zeta_{i,\lambda}\left\{C_9\,\tilde{V}_{L\lambda} - \frac{m_B^2}{q^2}\left[\frac{2\,\hat{m}_b}{m_B}C_{7\gamma}\,\tilde{T}_{L\lambda} - 16\pi^2 h_\lambda\right]\right\}$$

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

**Two possible issues**

1. $\zeta_i$ can miss interference between power corrections in FFs or $h_\lambda$
2. Is the treatment of theoretical error as experimental adequate?

# Obtention of error bands and comparison




## We use the *R*fit method

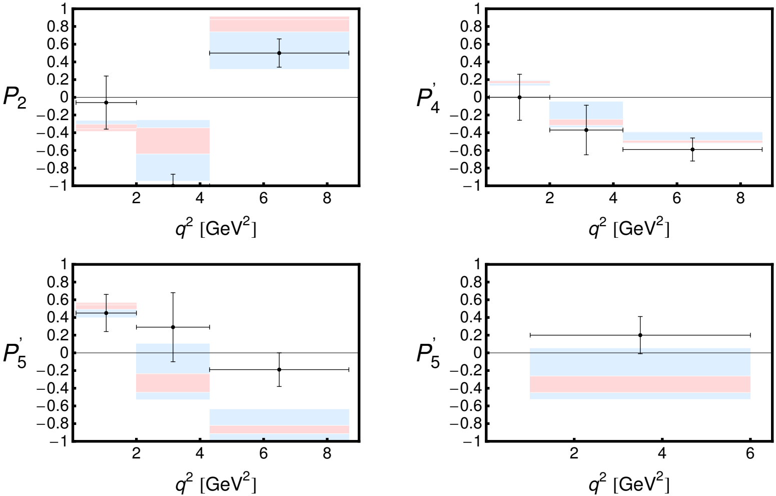
Method employed by **CKMfitter** for treating hadronic uncertainties

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



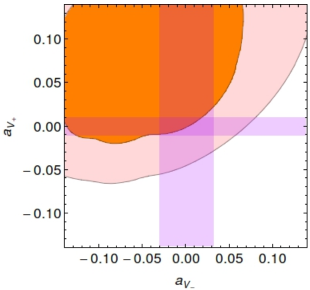

Red band Descotes-Genon *et al.* JHEP05(2013)137

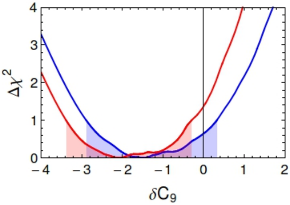
Blue band this analysis

- **Reminder:** I don't believe my treatment of charm over 6 GeV$^2$!

# The significance of the low-$q^2$ anomaly in our analysis

- We fit all the $P_i'$ observables in the bin [1,6] GeV$^2$




- Marginalized $\chi^2$ and 1-$\sigma$ intervals
  - Red "marginalized" $\chi^2(\delta C_9)$
  - Blue *Idem.* but $a_{V\_} = -0.056$ (-20% p.c.)

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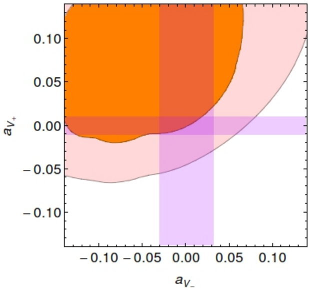


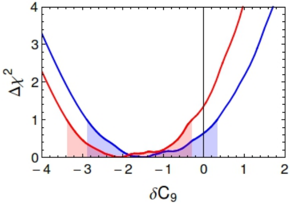


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- The anomaly could be *largely* accommodated in the SM through p.c.'s

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

- Charm contribution in $h_\lambda$ could also play a role

Lyon *et al.* arXiv:1406.0566, R. Zwicky talk tomorrow

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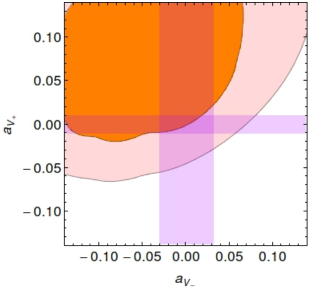


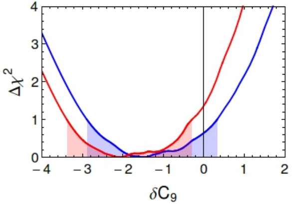


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- Similar conclusions were drawn from a bayesian analysis

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

  - Global analysis of all $b \to s\ell\ell$ data
  - Sizable power corrections (scale-factor method)

# Suppression of $H^{+}$ and new physics opportunities

- In the HQ/HE one finds that $H_{+} = \Lambda/m_b$ (for the $\bar{B}$ decay)
  - $V - A$ creates helicity left-handed (massless) *s*-quarks
  - Perturbative QCD corrections can't change helicity

Burdman *et al.* PRD63(2001)113008, Bauer *et al.*PRD63(2001)114020, Jäger *et al* JHEP 1305 (2013) 043, Hambrock *et al.* PRD89(2014)074014

1. This is realized in the form factors

$$\begin{aligned} T_{+}(q^2) &= \mathcal{O}(q^2) \times \mathcal{O}(\Lambda/m_b), \\ V_{+}(q^2) &= \mathcal{O}(\Lambda/m_b). \end{aligned}$$

2. But also on the potentially sizable long-distance $c\bar{c}$
   - We found that in **LCSRs** $h_{+|c\bar{c},\mathrm{LD}} \sim \mathcal{O}(\Lambda/m_b) h_{-|c\bar{c},\mathrm{LD}}$
3. And also the long-distance light quark contributions $H_V^{+} \sim \mathcal{O}(\Lambda^2/m_b^2)$

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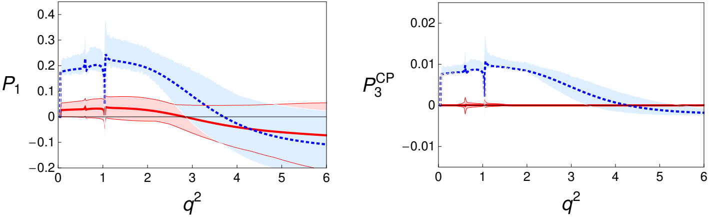
# "Superclean" observables and $C_7'$




- The observables $I_3$ and $I_9$ are proportional to

$$I_3 \propto \mathrm{Re}\left(H_+^V H_-^V\right) \propto \mathrm{Re}\left(C_7\, C_7'^*\right), \qquad I_9 \propto \mathrm{Im}\left(H_+^V H_-^V\right) \propto \mathrm{Im}\left(C_7\, C_7'^*\right),$$

  so they vanish unless $C_7' \neq 0$!!
- To study the sensitivity take the "clean" versions $P_1$ and $P_3^{CP}$ respectively
  - BSM 1: Take $C_7' = 0.1 C_7^{\rm SM}$ (left panel)
  - BSM 2: Take $C_7' = 0.01 \times i \times C_7^{\rm SM}$ (right panel)

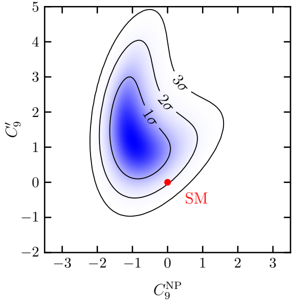
Observables are very sensitive to BSMs contributions surfacing in $C_7'$ for $q^2 < 3$ GeV$^2$

# What about the high $q^2$ region

- Especially suited for determining $C_9$
- Theoretical approach based on an HQET+OPE

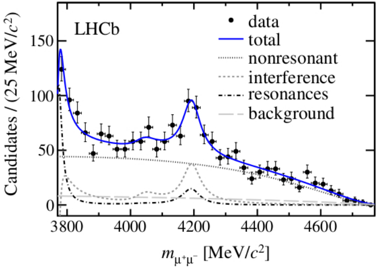
Grinstein *et al.* PRD70(2004)114005, Bobeth *et al.* JHEP1007(2010)098, Beylich *et al* EPJC71(2011)1635

- FFs can be calculated in LQCD!!




Horgan *et al.* PRL112(2014)212003

- **However:** Duality violations to the OPE could be large!!




Kaonic mode

R. Zwicky's talk tomorrow

# Conclusions

1. The $B \to K^* \ell\ell$ decay is a very rich probe of $b \to s$ FCNCs
2. There is a $\sim$4-$\sigma$ tension between 1 fb$^{-1}$ data and some SM predictions
   - New physics mechanisms invoquing $C_9$ can solve the anomaly
3. We adopt the *R*fit philosophy for the treatment of hadronic uncertainties
   - Our **predictions** reasonably agree with the SM
   - Alternative explanation within the SM in terms of power corrections
4. **How do we make progress?**
   - More data (2 fb$^{-1}$ on tape) and more finely binned!
   - Better knowledge on power corrections LCSRs or within EFT?
5. There are the Super-clean observables to access $C_7'$