Searching for new physics in rare B decays
Status after Moriond 2013

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@ NEXT meeting–RAL

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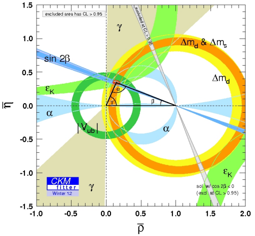
Flavor changing neutral currents (FCNC) in the SM

$$U_i \in \{u, c, t\}, \; q_U = +2/3 \qquad D_i \in \{d, s, b\}, \; q_D = -1/3$$

$$\mathcal{L}_{\rm c.c.} = \frac{g_2}{2\sqrt{2}} (\bar{u}, \bar{c}, \bar{t}) \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \gamma^\mu P_L \begin{pmatrix} d \\ s \\ b \end{pmatrix} W^+_\mu + {\rm h.c.}$$

- Chiral structure of c.c.: Only the left-handed components of the fields interact

- Complex and Unitary matrix⇒ **3 angles** and **1 phase**



$$V_{CKM} \simeq \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

$$\lambda = 0.2253(7), \quad A = 0.808(22),$$
$$\bar{\rho} = 0.132(22), \quad \bar{\eta} = 0.341(13)$$

- **The structure of the CKM matrix is extremely hierarchical!**

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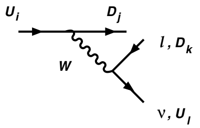
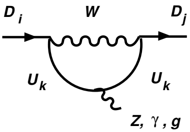
- **CC $U_i \to D_j$: Tree level**



- $H_1 \to H_2 H_3$
  $\mathcal{M} \sim G_F\, V_{ij} V_{kl}^*$,
  $V_{ij} V_{kl}^*$ can be $\mathcal{O}(1)$

- **FCNC $D_i \to D_j$: Loop**



- $H_1 \to H_2 G^0 \to H_2 \{H_3, \gamma, \bar{\ell}\ell\}$
  $\mathcal{M} \sim G_F\, g \sum_k V_{ki} V_{kj}^* f(M_k)$,
  $V_{ki} V_{kj}^* f(M_k)$ is $\mathcal{O}(\lambda_{\mathrm{CKM}}^2)\times$ Loop

- In the SM, FCNCs are suppressed w.r.t. CC interactions: **"Rare" decays!**

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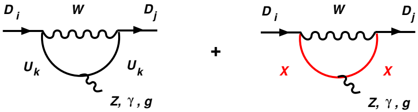
- **FCNC** $D_i \to D_j$: SM+new particles in the **Loop**



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$$\mathcal{M} \sim G_F\, g \left(\sum_k V_{ki} V^*_{kj} f(M_k) + \tilde{V}_{Xi} \tilde{V}^*_{Xj} f(M_X) \right)$$

- FCNCs are sensitive to the effects of virtual new particules!

Overview on status of "exclusive" rare B decays decays

- **"Exclusive decays"**: All the final products detected and identified
  $\bar{B} \to \bar{K}^* \ell^+ \ell^-$ ("exclusive") in opposition to $\bar{B} \to X_s \ell^+ \ell^-$ ("inclusive")
- Why $b \to s, d \ell^+ \ell^-$ transitions?
  - Leptonic and semi-leptonic transitions are theoretically accessible ("clean")
  - $b \to d$ transitions are suppressed by an extra $\lambda^2_{\rm CKM}$ factor: **More suppressed in the SM!**
- Branching fractions of $\sim 10^{-6}$ to $\sim 10^{-9}$ and relatively small number of events so far

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BaBar (433 fb^{-1})	U.L.	137±44	153±41	
Belle (605 fb^{-1})	U.L.	247±54	162±38	U.L.
CDF (∼10 fb^{-1})	U.L.	164±15	234±19	
LHCb (1.1-2.1 fb^{-1})	3.5-σ	900±34	1232±40	25±7
$10^7 \times \mathcal{B}$	$0.032^{+0.015}_{-0.012}$	$12.9^{+2.2}_{-2.1}$	5.0±0.4	0.23±0.06

n. b. **ATLAS** and **CMS** have also reported U. L.'s on $B^0_{d,s} \to \mu^+\mu^-$

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Model-independent analysis of semileptonic and exclusive $b \to s$ decay data

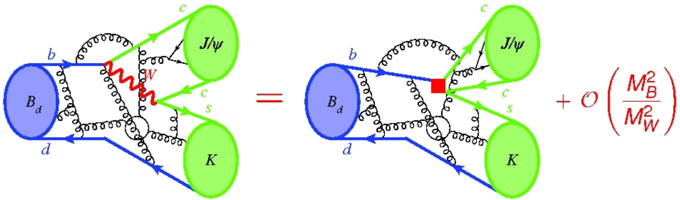
Search for BSM scenarios at the precision frontier!

- Careful study of the theoretical uncertainties
- High-precision of experimental data needed

The theory of the exclusive decays I: The weak Hamiltonian

- A theoretical treatment of the B meson decay starts with a separation of the different scales

Weak scale	B-meson mass, external momenta	"Long-distance" hadronic effects
$m_W,\ m_t,\ m_X \sim \mathcal{O}(100)$ GeV	$m_B \sim \mathcal{O}(5)$ GeV	$\Lambda_{QCD} \sim \mathcal{O}(0.5)$ GeV



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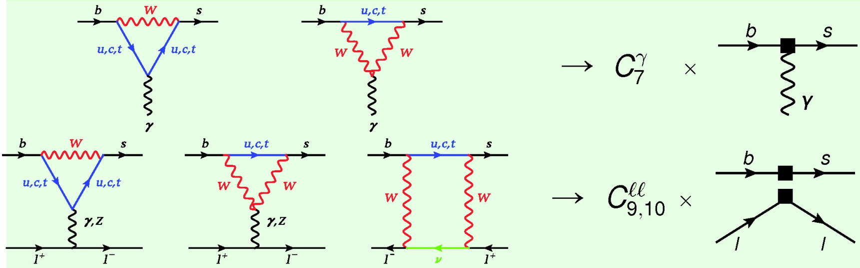
- At the hadronic scales interactions involving $\mathcal{O}(m_W)$ are approximately local (short-range)

The weak Hamiltonian $\mathcal{H}_w$

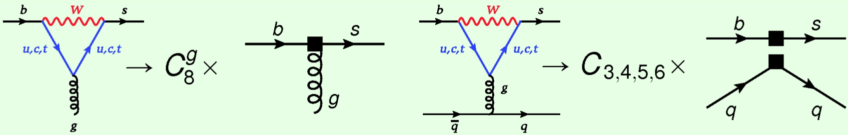
Integrate out $\mathcal{O}(m_W)$ DOF and construct a low-energy EFT

$b \to s + \gamma$ AND $b \to s + \ell^+\ell^-$



$$\mathcal{O}_7 = m_b[\bar{s}\,\sigma^{\mu\nu} P_R\, b]F_{\mu\nu} \qquad \mathcal{O}_{9,10} = [\bar{s}\,\gamma^{\mu} P_L\, b][\bar{\ell}\,\gamma_{\mu}(1,\ \gamma_5)\,\ell]$$

$b \to s + gluon$ AND $b \to s + \bar{q}q$



$$\mathcal{O}_8 = m_b[\bar{s}\,\sigma^{\mu\nu} P_R T^a\, b]G^a_{\mu\nu} \qquad \mathcal{O}_{3,4} = [\bar{s}\,\gamma^{\mu}(1,\ T^a)P_L\, b]\sum_q[\bar{q}\,\gamma_{\mu}(1,\ T^a)\,q]$$

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The weak Hamiltonian for $b \to s$ transitions

- In the SM we have

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

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

$$\mathcal{O}_3 = (\bar{s}b)_{V-A} \sum\nolimits_q (\bar{q}q)_{V-A}\,, \qquad \mathcal{O}_4 = (\bar{s}_i b_j)_{V-A} \sum\nolimits_q (\bar{q}_j q_i)_{V-A}\,,$$

$$\mathcal{O}_5 = (\bar{s}b)_{V-A} \sum\nolimits_q (\bar{q}q)_{V+A}\,, \qquad \mathcal{O}_6 = (\bar{s}_i b_j)_{V-A} \sum\nolimits_q (\bar{q}_j q_i)_{V+A}\,,$$

$$\mathcal{O}_7 = \frac{e}{4\pi^2}\, \hat{m}_b\, \bar{s}\sigma_{\mu\nu} P_R F^{\mu\nu} b\,, \qquad \mathcal{O}_8 = \frac{g_s}{4\pi^2}\, \hat{m}_b\, \bar{s}\sigma_{\mu\nu} P_R G^{\mu\nu} b\,,$$

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

- **Information on interactions/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_3	C_4	C_5	C_6	$C_7^{\rm eff}$	$C_8^{\rm eff}$	C_9	C_{10}
-0.144	1.060	0.011	-0.034	0.010	-0.040	-0.305	-0.168	4.24	-4.312

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- 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

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

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Scalar and pseudoscalar operators

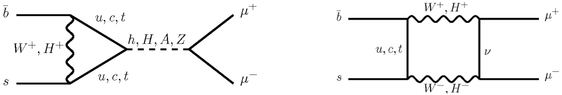
$$\mathcal{O}_S = \frac{\alpha_{\rm e.m}}{4\pi^2} \frac{\hat{m}_b}{m_W} (\bar{s} P_R b)(\bar{l}\, l)$$

$$\mathcal{O}_P = \frac{\alpha_{\rm e.m}}{4\pi^2} \frac{\hat{m}_b}{m_W} (\bar{s} P_R b)(\bar{l}\, \gamma_5\, l)$$

The $B^0_{s,d} \to \mu^+\mu^-$ decay

$B^0_{s,d} \to \mu^+\mu^-$: Scalar and pseudoscalar BSM contributions

- $B^0_{s,d} \to \mu^+\mu^-$ is **helicity-suppressed** in the **SM**!
- It becomes extremely sensitive to BSMs with sizable scalar and pseudoscalar contributions e.g. In the **MSSM** this decay can be easily enhanced at large $\tan\beta$
  Isiodori and Retico'01, Buras it et al.'02, ...



- For the B^0_s decay

$$\mathcal{B} \simeq \frac{G_F^2}{64\pi^3} f_{B_s} \tau_{B_s} m^3_{B_s} |V_{tb}V^*_{ts}| \times \left\{ |C_S - C'_S|^2 + |C_P - C'_P + 2\frac{m_\mu}{m_{B_s}}(C_{10} - C'_{10})|^2 \right\}$$

- The only **hadronic input** can be determined from the lattice QCD, $f_{B_s} = 234(10)$ MeV
- In the SM one finds ($C^{(\prime)}_{S,P} = C'_{10} = 0$ and $C_{10} = C^{SM}_{10}$)

$$\mathcal{B}(B^0_s \to \mu^+\mu^-)^{SM} = 3.23(27) \times 10^{-9}$$
$$\mathcal{B}(B^0_d \to \mu^+\mu^-)^{SM} = 1.07(10) \times 10^{-10}$$

Buras *et al.* '12
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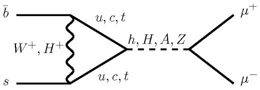

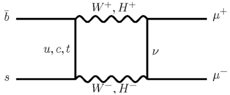

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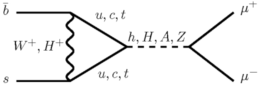

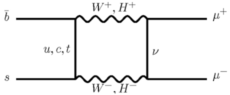

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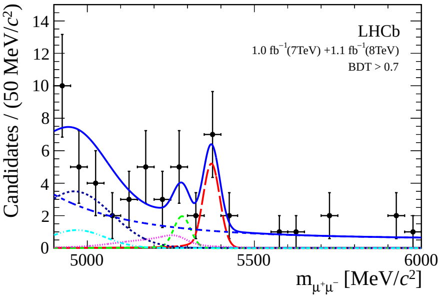
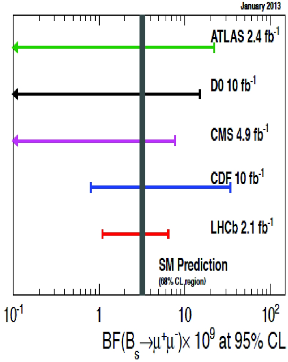


  - Full pdf; $B_s^0 \to \mu^+\mu^-$; $B_s^0 \to \mu^+\mu^-$

- Global effort
  Sabato Leo's talk at Moriond 2013



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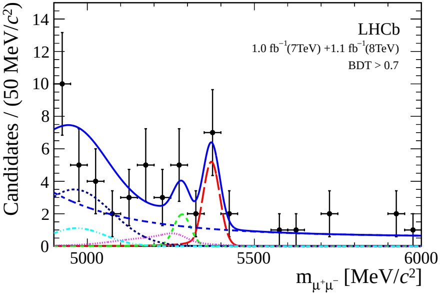
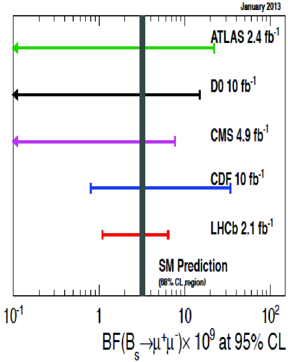


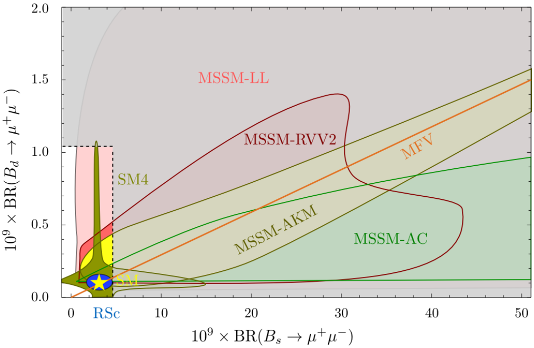


- Full pdf; $B^0_s \to \mu^+\mu^-$; $B^0_s \to \mu^+\mu^-$

$$\mathcal{B}(B^0_s \to \mu^+\mu^-)^{LHCb} = 3.2^{+1.5}_{-1.2} \times 10^{-9}$$
$$\mathcal{B}(B^0_d \to \mu^+\mu^-)^{LHCb} < 9.4 \times 10^{-10} \text{ @ } 95\% \text{ C. L.}$$

- **Experimental results strikingly close to SM predictions!**

$B^0_{s,d} \to \mu^+\mu^-$: Consequences



D. Straub Moriond '12 and '13

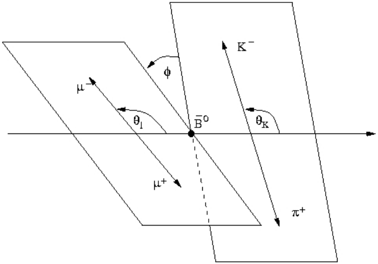
- Models giving large **scalar** and **pseudoscalar** contributions ruled out
  - Large tan β scenario in the MSSM
- BSM contributions to **semileptonic operators** (e.g. $\mathcal{O}_{10}^{(\prime)}$) are still possible
  - Much more accuracy required to constrain these models
  - Just 2 experimental branching fractions won't be enough: **Other processes are needed!**

The $\bar{B}^0 \to \bar{K}^* \ell^+ \ell^-$ decay

$\bar{B} \to \bar{K}^{*0}(\to K^-\pi^+)\ell^+\ell^-$ decay rate

- **4-body decay**
- There are 3 angles θ_K, θ_l and ϕ
- The invariant mass of the dilepton pair is a variable
  For the **muonic mode**:

$$0.0441 \text{ GeV}^2 < q^2 < 19.25 \text{ GeV}^2$$



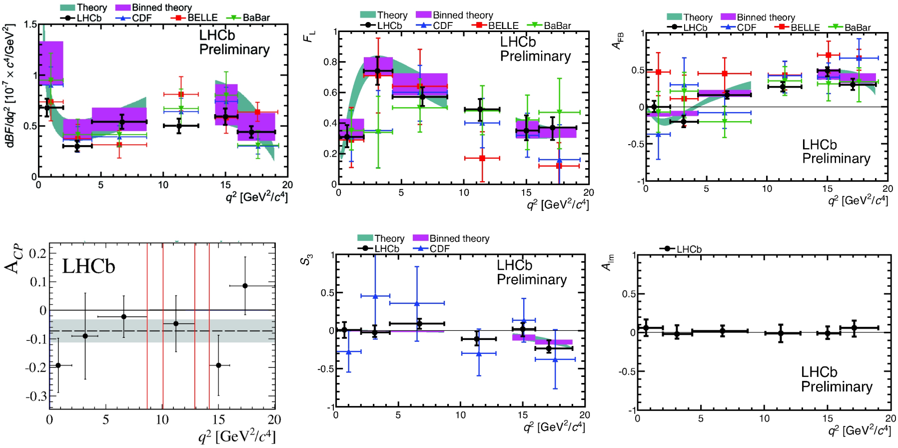
$$\frac{d^{(4)}\Gamma}{dq^2\, d(\cos\theta_l) d(\cos\theta_k) d\phi} = \frac{9}{32\pi}\Big(I_1^s \sin^2\theta_k + I_1^c \cos^2\theta_k + (I_2^s \sin^2\theta_k + I_2^c \cos^2\theta_k)\cos 2\theta_l$$
$$+ \quad I_3 \sin^2\theta_k \sin^2\theta_l \cos 2\phi + I_4 \sin 2\theta_k \sin 2\theta_l \cos\phi +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

$\bar{B} \to \bar{K}^{*0}(\to K^-\pi^+)\ell^+\ell^-$ decay has a very rich phenomenology

- Up to $I_i(q^2)$ **12** q^2-dependent observables
- The *CP*-partner adds other 12 independent observables
- A total of **24** observables per lepton mode!!

Experimental status

The best data is collected for the **muonic** mode



N. Serra 3rd Workshop on flavor in the LHC era 2013 (Valencia)

- **Towards a full angular analysis of the decay!**
- Experimental results are “roughly” consistent with the SM!

The theory of the $\bar{B} \to \bar{K}^* \ell^+ \ell^-$ decay

- The presence of a hadron in the final state complicates the theory

Careful and realistic theoretical analysis needed!

One has to know how far does he understand the hadronic effects

- In the $B \to K^* \ell^+ \ell^+$ we have the following contributions

$$\mathcal{M} \propto C_9 \, \langle K^*(k)|(\bar{s}\gamma^\mu P_L b)|B(p)\rangle \times \langle \ell^+ \ell^- |\bar{\ell}\gamma_\mu \ell|0\rangle$$

$$\mathcal{M} \propto \frac{1}{q^2} C_7 \, \langle K^*(k)|(\bar{s}\sigma^{\mu\nu} q_\nu P_R b)|B(p)\rangle \times \langle \ell^+ \ell^- |\bar{\ell}\gamma_\mu \ell|0\rangle$$

Hadronic matrix elements parameterized by **4+3** q^2 dependent functions: **form factors**

- At large $q^2 \simeq (m_B - m_{K^*})^2$ the form factors can be calculated in **LQCD**
- At low q^2 the form factors can be calculated in **LCSRs** and models

- The FFs are the major source of uncertainty in the treatment of exclusive B decays

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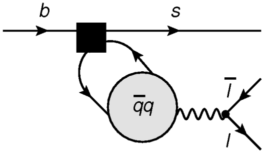
- Non-local contribution from the contraction of 4-quark operators $\mathcal{O}_{1-6}^{(c)}$ with the EM current



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

- This object is untractable in a model-independent manner in certain regions of q^2
- At $\sqrt{q^2} \sim m_{J/\Psi}$ it describes the decay through the charmonium resonances
  This is the reason why these regions of q^2 are cut-off from analyses

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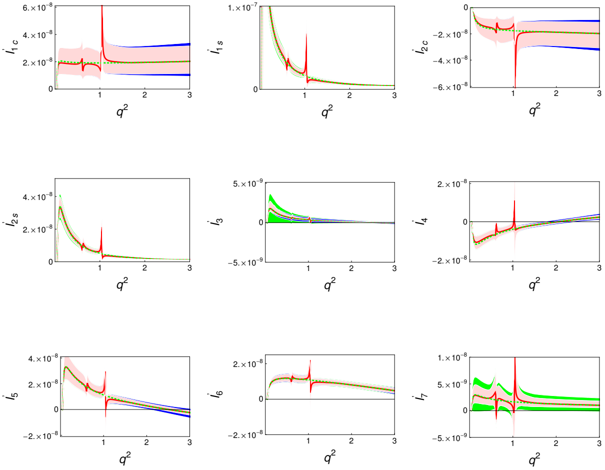
Two q^2 regions considered clean

- Low q^2, large recoil of the K^*: $q^2 < 6$ GeV^2
  Treated in **QCD factorization** and/or **SCET**$\Rightarrow$ Expansion in Λ/E_{K^*}
- High q^2, low recoil of the K^*: $q^2 > 15$ GeV^2
  Treated using **OPE+HQET**

- Much work has already been done on this decay
  Kruger, Sinha and Sinha '98, Beneke, Feldmann and Seidel'01'05, Kruger and Matias'05, Bobeth et al.'08, Altmannshofer et al.'08, Beylich et al.'11, Becirevic et al.'11, Matias and Virto'12, S. Jäger and JMC, . . .

SM predictions at low q^2 (μ-mode)

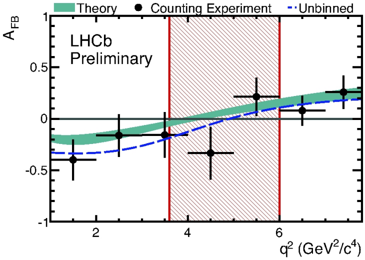


S. Jäger and JMC, arXiv:1212.2263

- **Theoretical uncertainties are large!**

Finding a "clean" set of observables

- The zero-crosssing q_0^2 of A_{FB}
  LHCb-CONF-2012-008



- The FF uncertainties cancel in the HQ limit at $q^2 = q_0^2$
  Ali et al '00
- In this limit, q_0^2 depends exclusively on $C_7^{(\prime)}$ and $C_9^{(\prime)}$
  Clean access to the short-distance FCNC of the decay!!

$$q^2_{0,\mathrm{th}} = 4.39(39)\ \mathrm{GeV}^2$$
$$q^2_{0,\mathrm{LHCb}} = 4.9^{+1.1}_{-1.3}\ \mathrm{GeV}^2$$

Th: Beneke et al. '00

- One can use ratios of $I_i^\prime s$ to cancel FF uncertainties in the HQ limit
  Kruger et al '05
- The P-basis is composed by the combinations
  Matias et al '12

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

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

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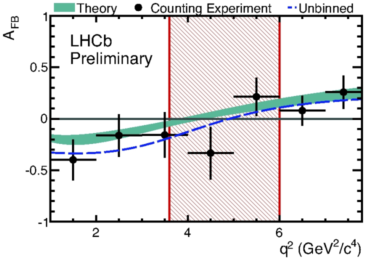

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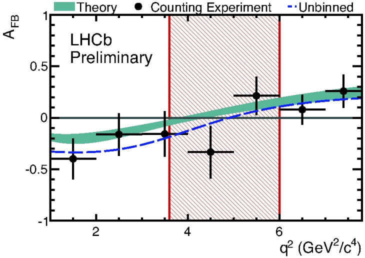

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Two "superclean" observables

Sensitivity to "wrong-helicity" photons at $q^2 \simeq 0$

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

vs.

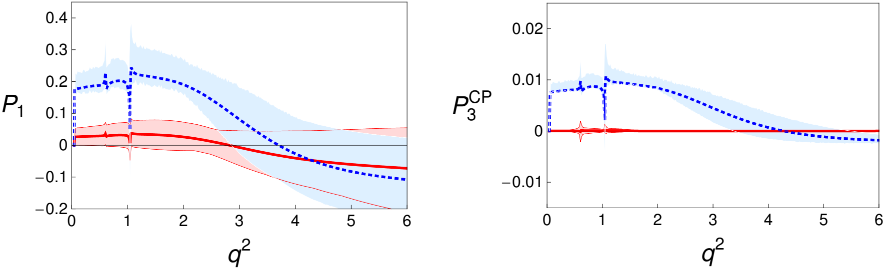
$$\mathcal{O}_7 = \frac{e}{4\pi^2}\,\hat{m}_b\,\bar{s}\sigma_{\mu\nu} P_R F^{\mu\nu} b$$

- In the SM decays into "wrong -helicity" photons are suppressed
  - $C_7' \simeq m_s/m_b \simeq 0.02$
  - Hadronic long-distance effects suppressed by by at least $\Lambda/m_B \simeq 10\%$
    S. Jäger and JMC'12
- The contribution of $\mathcal{O}_7^{(\prime)}$ is accompanied by $1/q^2$
  Sensitivity enhanced at very low q^2!
- The observables I_3 and I_9 are proportional to

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

  so they vanish unless $C_7' \neq 0$!!
- To study the sensitivity take the "clean" versions P_1 and P_3^{CP} respectively

Two "superclean" observables



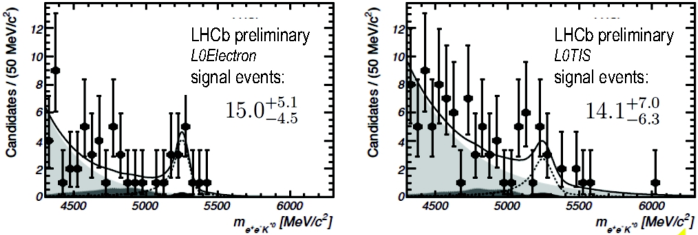
S. Jäger and JMC, arXiv:1212.2263

- 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)

These observables are very clean null-tests of the SM ($C_7' \simeq 0$) at very low q^2
Study the elctronic mode which is more sensitive to the photon pole!!

$B^0 \to K^{*0}e^+e^-$ BF at low dilepton mass

- **Results**



$$\mathcal{B}(B^0 \to K^{*0}e^+e^-)^{30-1000\,\mathrm{MeV}/c^2} = (3.1^{+0.9}_{-0.8}\ ^{+0.2}_{-0.3} \pm 0.2) \times 10^{-7}$$

stat. syst. BF(K^{*0} $J/\psi(e^+e^-)$) **Preliminary**

- In agreement with SM expectation (arXiv:1212.2263[hep-ph])
- Signal significance of 4.6σ including systematics
- It is planned to perform a full angular analysis with all the available LHCb data

Eli Ben-Haim Moriond QCD and High Energy Interactions, March12th 2013 16

Conclusions

- Rare B decays provides and empirical ground to test the SM and to explore NPs effects
- One has access to powerful tools dealing with the different scales in the problem
  - Weak hamiltonians integrate out $\Lambda \sim m_W$ vs.m_b
  - QCD factorization integrate out m_b vs. Λ_{QCD}
- The $B \to K^*(\to K\pi)\ell^+\ell^-$ is phenomenologically very rich
  Total of **24 observables** per leptonic mode
- Sound conclusions can be derived from the phenomenology only when the hadronic uncertainties are carefully tackled
- Everything quite SMish
  Too early: More data needed and further theoretical work to reduce hadronic uncertainties
- **Exciting times ahead!**
  In 2013 one can expect
  LHCb results on $B_s \to \ell^+\ell^-$ with the full 2012 data set!
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