The Decay $B \to K \ell^+ \ell^-$ and Model-Independent Analysis

Christian Wacker

TU Dortmund
Theoretische Physik III

based on
C. Bobeth, G. Hiller, D. van Dyk, CW (arXiv:1111.2558)

5th Annual Workshop of the Helmholtz Alliance
"Physics at the Terascale"
Bonn, 08. December 2011

technische universität
dortmund

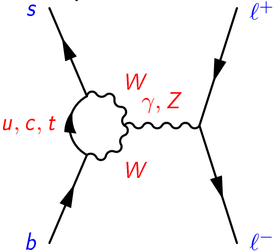
Introduction to $B^- \to K^- \ell^+ \ell^-$ decays

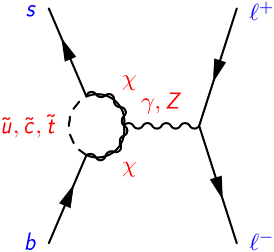
Searching for New Physics (NP)

- Standard Model (SM) very successful but incomplete
- extensions to SM predict additional particle content (e.g. SUSY)
- indirect search: NP contribution to loop processes
  $\Rightarrow$ need precise measurements and calculations

Parton Level

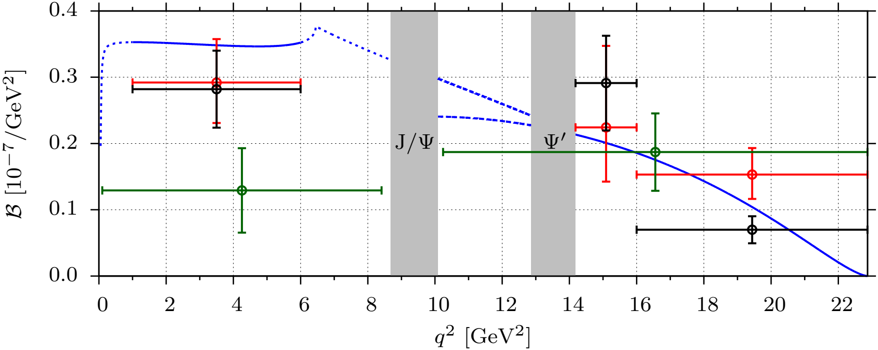
- $b \to s\, \ell^+ \ell^-$, mediated by Flavor Changing Neutral Currents (FCNCs)
- FCNCs forbidden at tree level in SM, but not through loops
  $\Rightarrow$ rare process





Introduction to $B^- \to K^- \ell^+ \ell^-$ decays

- differential branching fraction $\mathcal{B}$
- $\sqrt{q^2}$ = dilepton invariant mass
- SM prediction with form factors from Khodjamirian et al. (2010)
- experimental data from **BaBar** (2006) hep-ex/0604007, **Belle** arXiv:0904.0770 (2009) and **CDF** (2011) arXiv:1107.3753, total number events < 400



large recoil $q^2 \ll m_b^2$
Bobeth, Hiller, Piranishvili (2007)
arXiv:0709.4174

$c\bar{c}$-veto

low recoil $q^2 \approx m_b^2$
Bobeth, Hiller, van Dyk, CW (2011)
arXiv:1111.2558

Operator Product Expansion (OPE)

- two energy scales involved
  - weak scale $\mathcal{O}(m_W)$
  - hadronic scale $\mathcal{O}(m_b)$
- systematic and model-independent treatment with an OPE
- effective Hamiltonian for $b \to s\,\ell^+\ell^-$

$$\mathcal{H}_{\text{eff}} = -\frac{4\,G_{\text{F}}}{\sqrt{2}}\,V_{tb}\,V_{ts}^* \sum_{i=1}^{10} \mathcal{C}_i(\mu)\,\mathscr{O}_i(\mu) + \mathcal{O}(V_{ub}\,V_{us}^*)$$

  - Fermi-constant G_F from weak interactions
  - CKM elements $V_{tb}\,V_{ts}^*$ - top, charm dominant - up Cabibbo suppressed
  - Wilson coefficients $\mathcal{C}_i(\mu)$
  - local operators $\mathscr{O}_i(\mu)$
  - renormalization scale μ
- separation into long-distance $\mathscr{O}_i$ and short-distance $\mathcal{C}_i$ physics

Operator Product Expansion

- most relevant operators for $B \to K\ell^+\ell^-$

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

New Physics

- modifies Wilson coefficients (e.g. new heavy particles):

$$\mathcal{C}_i = \mathcal{C}_i^{\mathrm{SM}} + \mathcal{C}_i^{\mathrm{NP}}$$

- induces new operators (helicity-flipped, scalar, tensor, ...)
  - not investigated here

CP Violation (CPV)

- SM: CPV from complex-phase of CKM matrix
- SM: $\mathcal{C}_i$ real-valued in this basis
- complex-valued $\mathcal{C}_i \Rightarrow$ new source of CPV

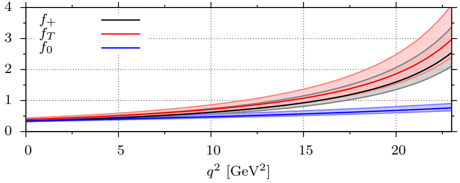
Hadronic Matrix Elements and Form Factors

Three Form Factors

- $\langle K\, |\bar{s}\, \gamma^\mu\, b|\, B \rangle \sim f_+, f_0$
- $\langle K\, |\bar{s}\, \sigma^{\mu\nu}\, b|\, B \rangle \sim f_T$
- biggest source of uncertainties

Khodjamirian et al.

arXiv:1006:4945



Improved Isgur-Wise Relation

- express QCD matrix elements through an OPE in $1/m_b$ using HQET fields
- relate HQET currents to quark currents

$$
\begin{aligned}
f_T(q^2) &= \frac{(m_B + m_K)m_B}{q^2}\, \kappa\, f_+(q^2) + \mathcal{O}\left(\alpha_s, \frac{\Lambda}{m_b}\right) \\
\kappa &= 1 + \mathcal{O}\left(\alpha_s^2\right) \text{ for } \mu = m_b
\end{aligned}
$$

- **reduction** of independent form factors: $3 \to 2$

Low Recoil Framework by Grinstein, Pirjol (2004) hep-ph/0404250

- improved Isgur-Wise relation
- OPE in $1/Q$ with $Q \in \{m_B, \sqrt{q^2}\}$
  - $\langle \mathscr{O}_{1\ldots 6,8} \rangle$ can be expressed through $\langle \mathscr{O}_{7,9,10} \rangle$
  - effective coefficients

$$\begin{aligned} \mathcal{C}_7^{\text{eff}} &= \mathcal{C}_7 + \mathcal{O}\left(\mathcal{C}_{3\ldots 6}, \alpha_s\, \mathcal{C}_{1,2,8}, \frac{m_c^2}{q^2}\right) \\ \mathcal{C}_9^{\text{eff}} &= \mathcal{C}_9 + \left(\frac{4}{3}\mathcal{C}_1 + \mathcal{C}_2\right) h\left(q^2\right) + \mathcal{O}\left(\mathcal{C}_{3\ldots 6}, \alpha_s\, \mathcal{C}_{1,2,8}, \frac{m_c^2}{q^2}\right) \end{aligned}$$

  - better control of non-perturbative matrix elements of operators $(\bar{s}\, \Gamma\, b)(\bar{q}\, \Gamma'\, q)$

Universal Short Distance Couplings at Low Recoil

for negligible lepton masses, $\ell \in \{e, \mu\}$

- amplitude for $B \to K\ell^+\ell^-$ depends only on

$$\rho_1 = \left|\kappa \, \frac{2\, m_b\, m_B}{q^2}\, \mathcal{C}_7^{\text{eff}} + \mathcal{C}_9^{\text{eff}}\right|^2 + |\mathcal{C}_{10}|^2$$

- ρ_1 known from $B \to K^*\ell^+\ell^-$ - Bobeth, Hiller, van Dyk (2010, 2011)
  arXiv:1006.5013, arXiv:1105.0376
- same sensitivity to ρ_1 in both decays
- CP asymmetry

$$A_{\text{CP}} = \frac{d\Gamma[\overline{B}^0 \to \overline{K}^0\ell^+\ell^-]/dq^2 - d\Gamma[B^0 \to K^0\ell^+\ell^-]/dq^2}{d\Gamma[\overline{B}^0 \to \overline{K}^0\ell^+\ell^-]/dq^2 + d\Gamma[B^0 \to K^0\ell^+\ell^-]/dq^2} = \frac{\rho_1 - \overline{\rho}_1}{\rho_1 + \overline{\rho}_1} = a_{\text{CP}}^{(1)}$$

universal in massless $B \to K^{(*)}\ell^+\ell^-$ decays

Constraining Wilson Coefficients

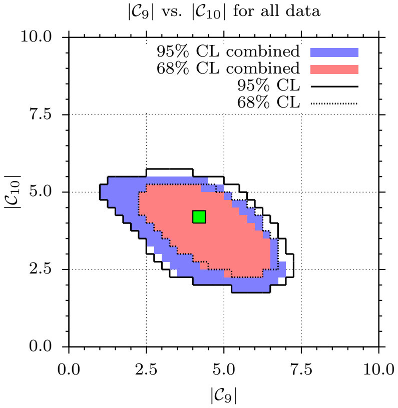
Procedure

- complex-valued Wilson coefficients $|\mathcal{C}_i|\, e^{i\,\phi_i}$
- scan over $\mathcal{C}_{7,9,10}$, leave other Wilson coefficients at SM values
- six-dimensional scan grid with about $6 \cdot 10^8$ sampling points
- determine χ^2 (distance) to experimental results
- reduction of information necessary:
  - calculate likelihood function $\mathcal{L} = \exp(-\chi^2/2)$
  - find sets that contain 1σ, 2σ, … of total likelihood
  - project sets onto two-dimensional planes, e.g. $|\mathcal{C}_9|$-$|\mathcal{C}_{10}|$

EOS

- software framework for the evaluation of flavor observables
- obtainable from http://project.het.physik.tu-dortmund.de/eos/

Constraining Wilson Coefficients - Results



Combined analysis

- colored areas include
  - $B \to K^* \ell^+ \ell^-$: Belle, CDF, LHCb
  - $B \to K \ell^+ \ell^-$: Belle, CDF
  - $B \to X_s \ell^+ \ell^-$: BaBar, Belle
- contour without $B \to K \ell^+ \ell^-$
- green square marks SM prediction
- slightly improved constraints on the Wilson coefficients
  - waiting for $B \to K \ell^+ \ell^-$ data from LHCb

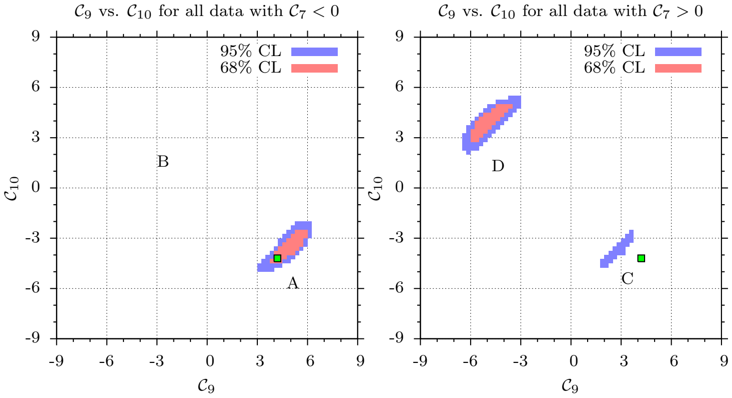
- $\mathrm{Br}(B_s \to \mu^+\mu^-) < 8 \cdot 10^{-9}$
- $1.0 \le |\mathcal{C}_9| \le 7.0$ @ 95 % CL
- $1.8 \le |\mathcal{C}_{10}| \le 5.5$ @ 95 % CL

Constraints on the Real Wilson Coefficients

- ignore all phases $\notin \{0, \pi\}$
- $\mathcal{C}_9$-$\mathcal{C}_{10}$ plane: ambiguity $C_7 \lessgtr 0$ ($C_7^{SM} < 0$)
- compatible with SM prediction
- Combined analysis:

q_0^2: zero-crossing of A_{FB} in $B \to K^* \ell^+ \ell^-$:

- $\mathcal{C}_7 < 0$: $q_0^2 > 2.6\ \text{GeV}^2$
- $\mathcal{C}_7 > 0$: $q_0^2 > 1.7\ \text{GeV}^2$



Summary and Outlook

Summary

- analysis of $B \to K\ell^+\ell^-$ at low recoil with heavy quark OPE by Grinstein and Pirjol
- same short distance coupling for $B \to K\ell^+\ell^-$ as in $B \to K^*\ell^+\ell^-$ (massless case)
- present $B \to K\ell^+\ell^-$ data already contribute to combined analysis

Outlook

- 2011: LHCb collected $> 1\,\mathrm{fb}^{-1}$, equivalent to about 1000 events for each channel: $B \to K\mu^+\mu^-$ and $B \to K^*\mu^+\mu^-$

Backup

Extended Operator Bases

- helicity flipped-operators

$$\mathscr{O}_{7'} \propto [\bar{s}\,\sigma^{\mu\nu}\,P_L\,b\,]\,F_{\mu\nu} \qquad \mathscr{O}_{9'(10')} \propto [\bar{s}\,\gamma^{\mu}\,P_R\,b][\bar{\ell}\,\gamma_{\mu}\,(\gamma_5)\,\ell]$$

- scalar and pseudoscalar operators

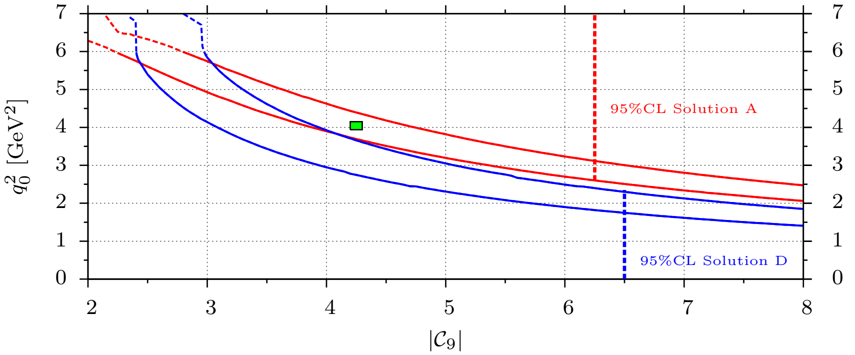
$$\mathscr{O}_{S,S'} \propto [\bar{s}\,P_{R,L}\,b][\bar{\ell}\,\ell] \qquad \mathscr{O}_{P,P'} \propto [\bar{s}\,P_{R,L}\,b][\bar{\ell}\,\gamma_5\,\ell]$$

- tensor and pseudotensor operators

$$\mathscr{O}_{T} \propto [\bar{s}\,\sigma_{\mu\nu}\,b][\bar{\ell}\,\sigma^{\mu\nu}\,\ell] \qquad \mathscr{O}_{T5} \propto [\bar{s}\,\sigma_{\mu\nu}\,b][\bar{\ell}\,\sigma^{\mu\nu}\,\gamma_5\,\ell]$$

A_{FB} zero crossing of $B \to K^* \ell^+ \ell^-$

- root of the forward-backward asymmetry



- $\mathcal{C}_7 > 0$: $q_0^2 > 1.7\text{GeV}^2$
- $\mathcal{C}_7 < 0$ - SM-like: $q_0^2 > 2.6\text{GeV}^2$

Performance of Improved Isgur-Wise Relation at Low Recoil

$$R_T(q^2) := \frac{q^2}{m_B(m_B + m_K)} \frac{f_T(q^2)}{f_+(q^2)}$$