$B \to K \ell^+ \ell^-$ and EOS

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Theoretische Physik III

based on
Bobeth, Hiller, van Dyk, CW (DO-TH 11/23, to appear)

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Introduction

Searching for New Physics (NP)

- Standard Model (SM) very successful but incomplete (unification with gravity, hierarchy problem, ...) $\Rightarrow$ search for new physics
- extensions to SM predict additional particle content (e.g. supersymmetry)
- direct search: available energy $\simeq$ particle mass
- indirect search: NP contribution to loop processes (lower energy) $\Rightarrow$ need precise measurements and calculations

Rare B Decays

- small branching ratio: 10^{-5} $(B \to K^* \gamma)$ to 10^{-8} $(B_s \to \mu^+ \mu^-)$ $\Rightarrow$ sensitive to new physics
- great number of B mesons at B factories (e.g. BaBar, Belle) and LHCb

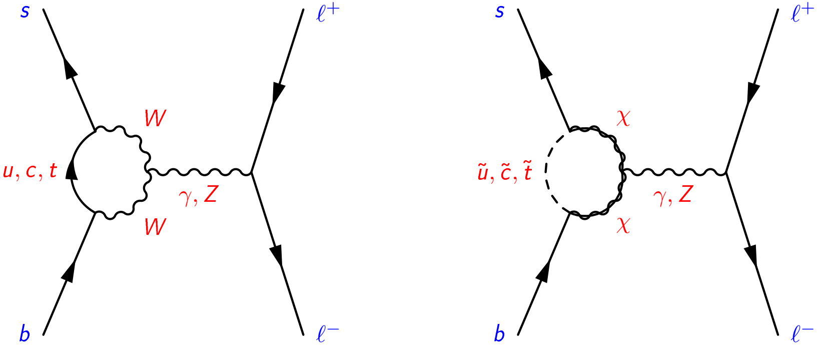
Introduction to $B^- \to K^- \ell^+ \ell^-$ decays

$B^- = (b\,\overline{u})$

$K^- = (s\,\overline{u})$

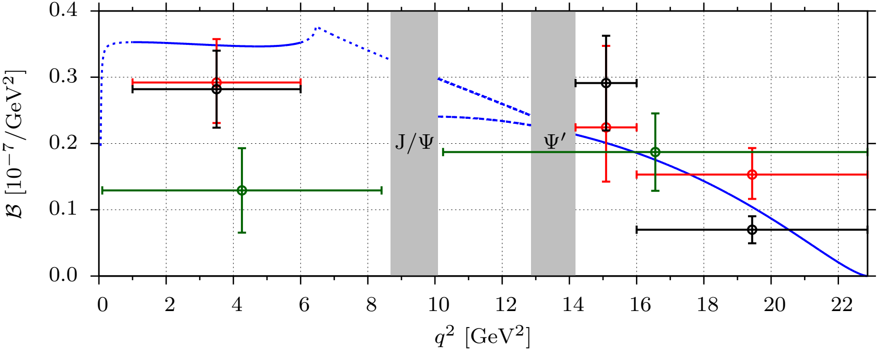
$\ell \in \{e, \mu, \tau\}$

- 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
- GIM mechanism & FCNCs $\Rightarrow$ 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 $q^2 \approx m_b^2$
this work

Operator Product Expansion (OPE)

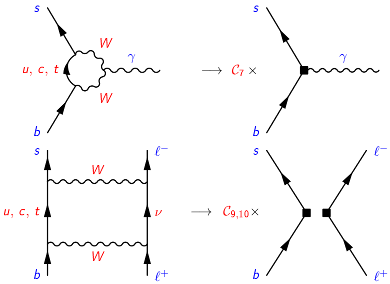
- two energy scales involved
  - weak scale $\mathcal{O}(m_W)$
  - hadronic scale $\mathcal{O}(m_b)$
- systematic and model-independent treatment with an OPE
- effective Hamiltonian for $b \to s\,\ell^+\ell^-$

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

  - 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 $\mathcal{O}_i(\mu)$
  - renormalization scale μ

Operator Product Expansion

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



- calculate amplitude twice at $\mathcal{O}(m_W)$
  - full theory
  - effective Hamiltonian
- match the results ⇒ $\mathcal{C}_i$
- QCD asymptotically free
  ⇒ perturbative methods apply
- heavy particles (top, W-, Z-boson) integrated out
- use Renormalization Group Equations (RGE) to evolve $\mathcal{C}_i$ to scale $\mathcal{O}(m_b)$
  - sum large logarithms $\ln(m_W/\mu) \approx 3$
- separation into long-distance $\mathcal{O}_i$ 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

- modified Wilson coefficients (e.g. new heavy particles)
- new operators (helicity-flipped, scalar, tensor, ...)
  - not investigated

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

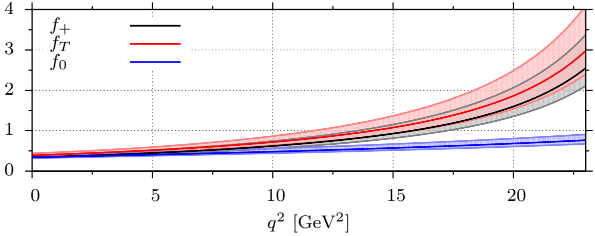
- $\langle K \,|\bar{s}\,\gamma^{\mu}\, b|\, B\rangle \sim f_{+}, f_0$
- $\langle K \,|\bar{s}\,\sigma^{\mu\nu}\, b|\, B\rangle \sim f_T$
- biggest source of uncertainties
  - reduction through form factor relation

Calculation

- different parametrizations
- non-perturbative methods
- Light Cone Sum Rules (LCSR)
  - large recoil region
  - expansion in $1/E_K$
- Lattice
  - low recoil region
  - $E_K <$ inverse lattice spacing

LCSR - Khodjamirian et al. [KMPW]

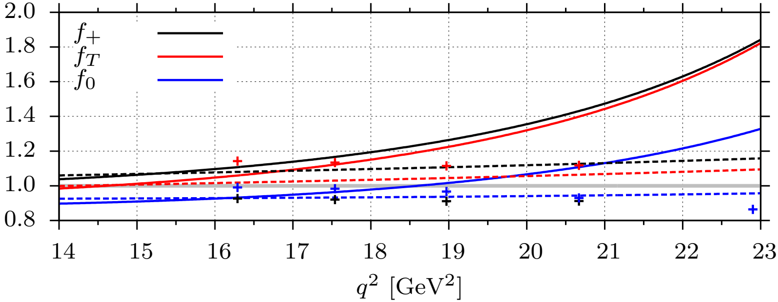
arXiv:1006:4945



Comparison of Form Factors

Form Factors Normalized to [KMPW]

- solid - LCSR - Ball, Zwicky [BZ] hep-ph/0406232
- dashed - LCSR - Bharucha, Feldmann, Wick [BFW] arXiv:1004.3249
- points - Lattice - Liu et al. [Liu] (preliminary) arXiv:1101.2726



- [KMPW], [BFW] and [Liu] in good agreement
  - Use [KMPW] (known uncertainties)

Form Factor Relation hep-ph/0404250

Heavy Quark Effective Theory (HQET)

- meson with heavy and light quark, e.g. $B^- = (b\bar{u})$
- limit $m_b \to \infty$ with velocity fixed

Improved Isgur-Wise Relation

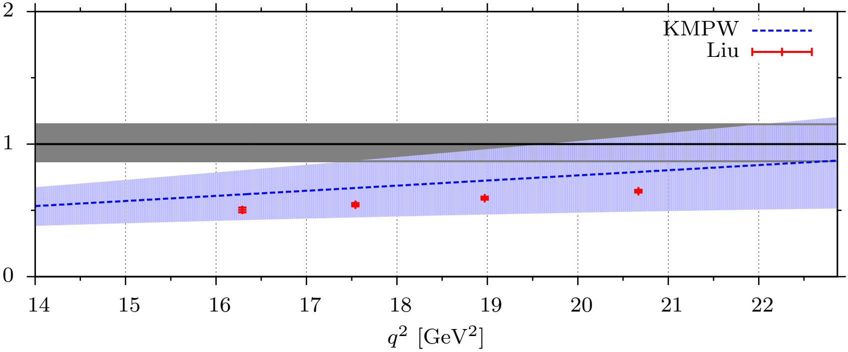
- express QCD matrix elements through an OPE in $1/m_b$ using HQET fields
- relate HQET currents to quark currents

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

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

Performance of Improved Isgur-Wise Relation at Low Recoil

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



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 $(\bar{s}\, b)(\bar{q}\, q)$

Universal Short Distance Couplings at Low Recoil

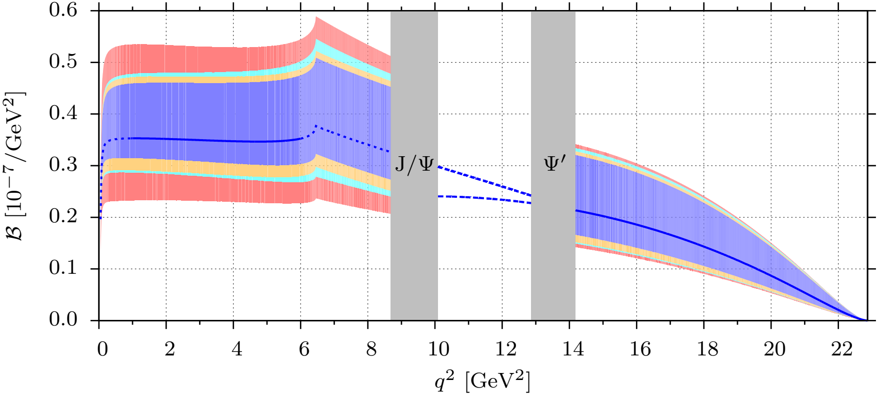
for negligible lepton masses, $\ell \in \{e, \mu\}$

- amplitude for $B \to K\ell^+\ell^-$ depends only on ρ_1
  ρ_1: certain combination of Wilson coefficients

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

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

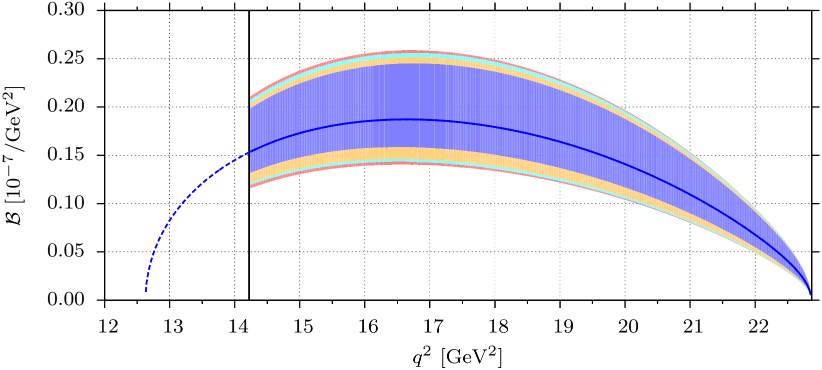
Branching Ratio $B^- \to K^-\mu^+\mu^-$



uncertainties

- form factors
- CKM matrix elements, λ and A of Wolfenstein parametrization
- short-distance physics μ
- sub-leading contributions $\mathcal{O}(1/m_b)$

Branching Ratio $B^- \to K^-\tau^+\tau^-$



- sensitive to $|\mathcal{C}_{10}|$
- not measured yet (Super B Factories)

Angular Distribution $B \to K\ell^+\ell^-$

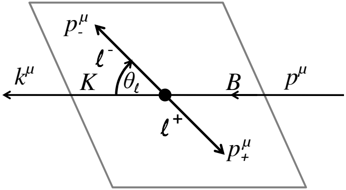
General Result

$$\frac{d^2\Gamma}{dq^2\, d\cos\theta_\ell} = \frac{d\Gamma}{dq^2}\left(\frac{F_H}{2} + A_{FB}\cos\theta_\ell + \frac{3}{4}(1 - F_H)\sin^2\theta_\ell\right)$$

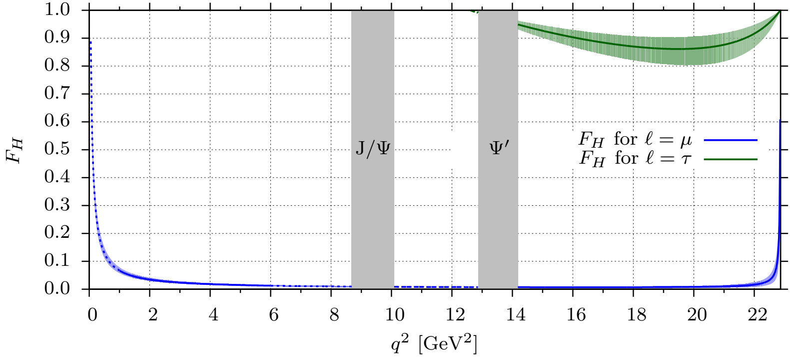
- SM: forward-backward asymmetry A_{FB} vanishes
- flat term F_H: deviation from

$$\frac{d^2\Gamma}{dq^2\, d\cos\theta_\ell} \propto \sin^2\theta$$

Kinematics - lepton CMS



Flat Term F_H



- normalized observable ⇒ cancellation of hadronic uncertainties
- negligible for electrons

CP asymmetry

- massless case $\ell \in \{e, \mu\}$

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

- $\rho_1 \to \overline{\rho}_1$: conjugate weak phases
- $a_{\mathrm{CP}}^{(1)}$ known from $B \to K^* \ell^+ \ell^-$ - Bobeth, Hiller, van Dyk (2011) arXiv:1105.0376
- CP asymmetry universal in massless $B \to K^{(*)} \ell^+ \ell^-$ decays

EOS

Overview

- software framework for the evaluation of flavor observables
- created by Danny van Dyk
- EOS collaboration: Frederik Beaujean, Christoph Bobeth, Danny van Dyk, CW
- written C++11

Features

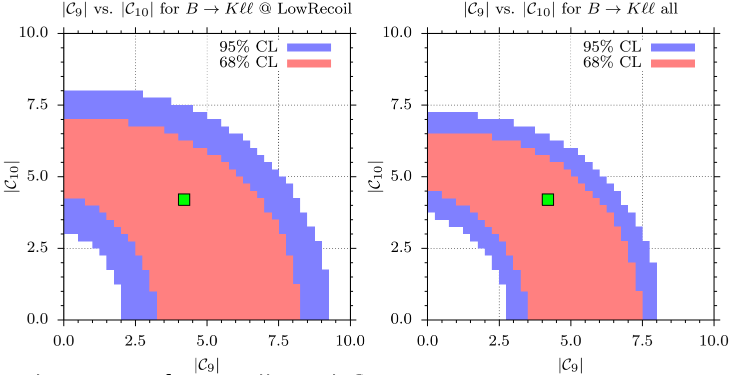
- NNLO RGE running of Wilson coefficients, α_s and $\overline{\mathrm{MS}}$ quark masses
- calculation of parameter constraints (e.g. for Wilson coefficients $\mathcal{C}_i$)
- includes all observables presented and many more:
  - $B \to K^* \ell^+ \ell^-$
  - $B_{s,d} \to \ell^+ \ell^-$
  - $B \to K^* \gamma$

obtainable from http://project.het.physik.tu-dortmund.de/eos/

Constraining Wilson Coefficients

- complex-valued Wilson coefficients $|\mathcal{C}_i|\, e^{i\,\phi_i}$, i.e. CP violation beyond SM
- 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. $|\mathcal{C}_9|$-$|\mathcal{C}_{10}|$

Constraining Wilson Coefficients - $B \to K\,\mu^+\mu^-$



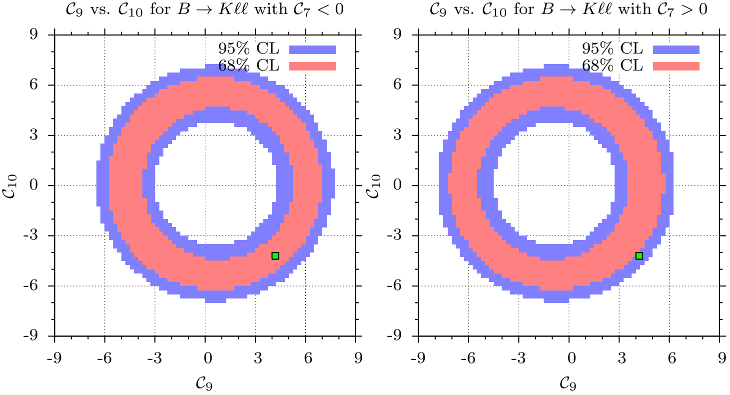
- branching ratio from Belle and CDF
- green mark represents SM prediction
- branching ratio $B \to K\mu^+\mu^-$ depends solely on

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

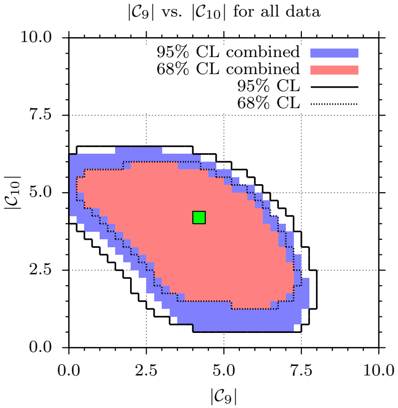
  - weak sensitivity to ϕ_9
  - no sensitivity to ϕ_{10}

Constraints on the Real Wilson Coefficients - $B \to K\,\mu^+\mu^-$

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



Constraining Wilson Coefficients



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 $B \to K \ell^+ \ell^-$
- no data from LHCb on $B \to K \ell^+ \ell^-$ yet
  $\Rightarrow$ low impact on combined analysis
- improved constraints on the Wilson coefficients

Summary and Outlook

Summary

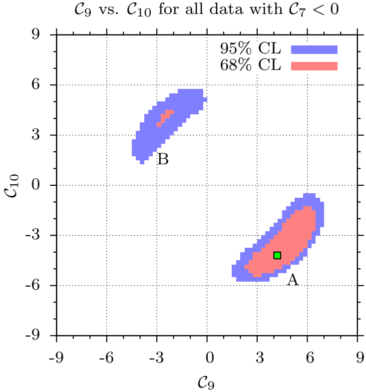
- analysis of $B \to K\ell^+\ell^-$ at low recoil with heavy quark OPE by Grinstein and Pirjol
- same short distance coupling for $B \to K\ell^+\ell^-$ as in $B \to K^*\ell^+\ell^-$ (massless case)
- present $B \to K\ell^+\ell^-$ data already contribute to combined analysis

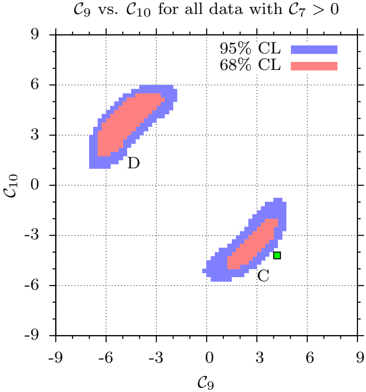
Outlook

- 2011: LHCb collected $> 1\,\mathrm{fb}^{-1}$, equivalent to 1000 events of $B \to K\mu^+\mu^-$
- Bayesian analysis, better estimation of uncertainties
  in collaboration with Beaujean, Bobeth, van Dyk (to appear)

Backup

Real Contraints - Combined Analysis





Extended Operator Bases

- helicity flipped-operators

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

- scalar and pseudoscalar operators

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

- tensor and pseudotensor operators

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