$b \to s + \bar{\ell}\ell$

PHENOMENOLOGY

@ HIGH-q^2

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Rare *B* decays @ low recoil (bsll2011)
DESY - Hamburg

OUTLINE

1) Effective theory (EFT) of $\Delta B = 1$ FCNC decays

   A) In the Standard Model (SM)

   B) Beyond the SM (BSM)

2) Exclusive $B \to V_{on-shell} (\to P_1 P_2) + \bar{\ell}\ell$

   A) Kinematics and observables in angular distribution

   B) High-q^2: SM Op's-basis + Fit

   C) High-q^2: BSM

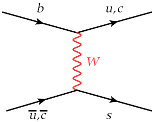
3) Exclusive $B \to P + \bar{\ell}\ell$

EFT of $\Delta B = 1$ decays in SM and beyond

$\Delta B = 1$ EFT in the SM (for $b \to s$)

I) decoupling (OPE) of heavy particles ($W, Z, t, \ldots$) @ EW scale: $\mu_{EW} \gtrsim M_W$
$\to$ factorisation into short-distance: C_i and long-distance: $\mathcal{O}_i$

II) RG-running to lower scale: $\mu_b \sim m_b$ $\to$ resums large log's: $[\alpha_s \ln(\mu_b/\mu_{EW})]^n$



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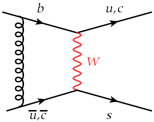
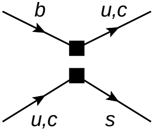
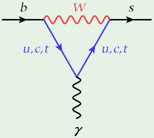
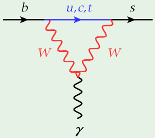


$\longrightarrow \quad C_{1,2}^{(0)} + \frac{\alpha_s}{4\pi} C_{1,2}^{(1)} \quad \times$

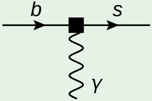


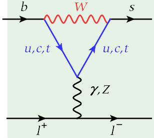
Most relevant for $b \to s + \bar{\ell}\ell$

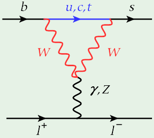


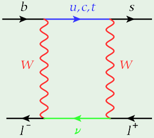


$\longrightarrow \quad C_7^{\gamma} \quad \times$

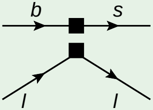








$\longrightarrow \quad C_{9,10}^{\ell\ell} \quad \times$



SM operator List

. . . using CKM unitarity

$$\mathcal{L}_{\rm SM} \sim \frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \left(\mathcal{L}_{\rm SM}^{(t)} + \hat{\lambda}_u \, \mathcal{L}_{\rm SM}^{(u)} \right), \qquad \hat{\lambda}_u = V_{ub} V_{us}^* / V_{tb} V_{ts}^*$$

$$\mathcal{L}_{\rm SM}^{(u)} = C_1 (\mathcal{O}_1^c - \mathcal{O}_1^u) + C_2 (\mathcal{O}_2^c - \mathcal{O}_2^u)$$

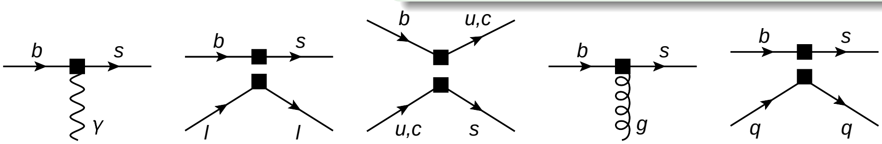
$\mathcal{O}_{1,2}^{u,c}$ = curr.-curr.: $b \to s \{\bar{u}u, \, \bar{c}c\}$

$\Rightarrow$ CP-violation in the SM is tiny

$$\mathrm{Im}[\hat{\lambda}_u] \approx \lambda^2 \bar{\eta} \sim 10^{-2}$$

$$\mathcal{L}_{\rm SM}^{(t)} = C_1 \mathcal{O}_1^c + C_2 \mathcal{O}_2^c + \sum_{i>2} C_i \mathcal{O}_i$$

$\mathcal{O}_7^\gamma$	= electr.magn.	$b \to s \, \gamma$
$\mathcal{O}_{9,10}^{\ell\ell}$	= semi-lept.	$b \to s \, \bar{\ell}\ell$
$\mathcal{O}_{1,2}^c$	= curr.-curr.	$b \to s \, \bar{c}c$
$\mathcal{O}_8^g$	= chromo.magn.	$b \to s \, g$
$\mathcal{O}_{3,4,5,6}$	= QCD-peng.	$b \to s \, \bar{q}q$, $q = \{u, d, s, c, b\}$
$\mathcal{O}_{3,4,5,6}^Q$	= QED-peng.	$b \to s \, \bar{q}q$, $q = \{u, d, s, c, b\}$
$\mathcal{O}_b$	= QED-box	$b \to s \, \bar{b}b$



MODEL-DEP. 1) decoupling of new heavy particles @ NP scale: $\mu_{NP} \gtrsim M_W$

2) RG-running to lower scale $\mu_b \sim m_b$ (potentially tower of EFT's)

MODEL-INDEP. extending SM EFT-Lagrangian $\rightarrow$ ...

... beyond the SM:

- $\Rightarrow$??? ... additional light degrees of freedom ($\Leftarrow$ not pursued in the following)
- $\Rightarrow$ ΔC_i ... NP contributions to SM C_i
- $\Rightarrow$ $\sum_{\text{NP}} C_j \mathcal{O}_j(???)$ ... NP operators (e.g. $C'_{7,9,10}$, $C^{(\prime)}_{S,P}$, ...)

$$\mathcal{L}_{\text{EFT}}(\mu_b) = \mathcal{L}_{\text{QED}\times\text{QCD}}(u, d, s, c, b,\ e, \mu, \tau,\ ???)$$
$$+ \frac{4G_F}{\sqrt{2}} V_{\text{CKM}} \sum_{\text{SM}} (C_i + \Delta C_i)\mathcal{O}_i + \sum_{\text{NP}} C_j \mathcal{O}_j(???)$$

Beyond the SM operator list

Frequently considered in model-(in)dependent searches: $b \to s + \bar{\ell}\ell$

SM' = χ-flipped SM analogues

$$\mathcal{O}_{7',8'}^{\gamma,g} = \frac{(e, g_s)}{16\pi^2} m_b [\bar{s}\,\sigma_{\mu\nu} P_L (T^a)\, b](F, G^a)^{\mu\nu}, \qquad \mathcal{O}_{9',10'}^{\ell\ell} = \frac{\alpha_e}{4\pi}[\bar{s}\,\gamma^\mu P_R\, b][\bar{\ell}\,(\gamma^\mu, \gamma^\mu\gamma_5)\,\ell],$$

S + P = scalar + pseudoscalar

$$\mathcal{O}_{S,S'}^{\ell\ell} = \frac{\alpha_e}{4\pi}[\bar{s}\, P_{R,L}\, b][\bar{\ell}\,\ell], \qquad \mathcal{O}_{P,P'}^{\ell\ell} = \frac{\alpha_e}{4\pi}[\bar{s}\, P_{R,L}\, b][\bar{\ell}\,\gamma_5\,\ell],$$

T = tensor

$$\mathcal{O}_{T}^{\ell\ell} = \frac{\alpha_e}{4\pi}[\bar{s}\,\sigma_{\mu\nu}\, b][\bar{\ell}\,\sigma^{\mu\nu}\,\ell], \qquad \mathcal{O}_{TE}^{\ell\ell} = \frac{\alpha_e}{4\pi}\, i\,\varepsilon^{\mu\nu\alpha\beta}[\bar{s}\,\sigma_{\mu\nu}\, b][\bar{\ell}\,\sigma_{\alpha\beta}\,\ell],$$

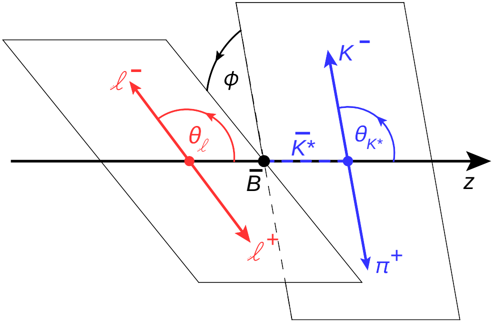
- Dirac-structures BSM: right-handed currents, (pseudo-) scalar and/or tensor interactions
- usually added to $\mathcal{L}_{\mathrm{SM}}^{(t)}$

$\Rightarrow$ EFT starting point for calculation of observables
!!! Non-PT input required when evaluating matrix elements

$$B \to V_{on-shell}(\to P_1 P_2) + \bar{\ell}\ell$$

KINEMATICS

- for on-resonance V decays
  $\to$ narrow width approximation
  $\to$ 4 kinematic variables
  (off-reson. 5 kin. variables)
- $Br(K^* \to K\pi) \approx 99\,\%$
- $\bar{B}^0 \to \bar{K}^{*0}(\to K^-\pi^+, \bar{K}^0\pi^0) + \bar{\ell}\ell$
  and CP-conjugated decay:
  $B^0 \to K^{*0}(\to K^+\pi^-, K^0\pi^0) + \bar{\ell}\ell$
- similarly $B_s \to \phi(\to K^+K^-) + \bar{\ell}\ell$



$$\bar{B}^0(p_B) \to \bar{K}^{*0}_{on-shell}(p_{K^*})[\to K^-(p_K) + \pi^+(p_\pi)] \;+\; \bar{\ell}(p_{\bar{\ell}}) + \ell(p_\ell)$$

1) $q^2 = m^2_{\bar{\ell}\ell} = (p_{\bar{\ell}} + p_\ell)^2 = (p_B - p_{K^*})^2$ $\qquad 4m^2_\ell \leqslant q^2 \leqslant (M_B - M_{K^*})^2$

2) $\cos\theta_\ell$ with $\theta_\ell \angle(\vec{p}_B, \vec{p}_{\bar{\ell}})$ in $(\bar{\ell}\ell)$-c.m. system $\qquad -1 \leqslant \cos\theta_\ell \leqslant 1$

3) $\cos\theta_{K^*}$ with $\theta_{K^*} \angle(\vec{p}_B, \vec{p}_K)$ in $(K\pi)$-c.m. system $\qquad -1 \leqslant \cos\theta_{K^*} \leqslant 1$

4) $\phi\ \angle(\vec{p}_K \times \vec{p}_\pi, \vec{p}_{\bar{\ell}} \times \vec{p}_\ell)$ in B-RF $\qquad -\pi \leqslant \phi \leqslant \pi$

DIFF. ANGULAR DISTRIBUTION

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

$I_i^{(k)}(q^2) = q^2$-dependent "ANGULAR OBSERVABLES"

$\Rightarrow 2 \times (12 + 12) = 48$ when measuring separately

A) decay + CP-conjugate decay

B) for each $\ell = e, \mu$ (τ's are interesting too!!!)

CP-conjugated decay: $d^4\bar{\Gamma}$ from $d^4\Gamma$ by replacing

$$I_{1,2,3,4,7}^{(k)} \quad \to \quad + \bar{I}_{1,2,3,4,7}^{(k)}[\delta_W \to -\delta_W], \qquad \text{CP-even}$$

$$I_{5,6,8,9}^{(k)} \quad \to \quad - \bar{I}_{5,6,8,9}^{(k)}[\delta_W \to -\delta_W], \qquad \text{CP-odd}$$

with $\ell \leftrightarrow \bar{\ell} \Rightarrow \theta_\ell \to \theta_\ell - \pi$ and $\phi \to -\phi$ and weak phases δ_W conjugated

OBSERVABLES - I

- for (SM + χ-flipped) operators and $m_\ell = 0$: $I_1^s = 3 I_2^s$, $I_1^c = -I_2^c$, $I_6^c = 0$
- in presence of scalar and/or tensor operators: $I_6^c \neq 0$

COMBINING DECAY + CP-CONJUGATED DECAY

CP-averaged $$S_i^{(k)} = \left[I_i^{(k)} + \bar{I}_i^{(k)} \right] \Big/ \frac{d(\Gamma + \bar{\Gamma})}{dq^2}$$

CP asymmetries $$A_i^{(k)} = \left[I_i^{(k)} - \bar{I}_i^{(k)} \right] \Big/ \frac{d(\Gamma + \bar{\Gamma})}{dq^2}$$

- normalisation to CP-ave rate $\rightarrow$ reduce form factor dependence
  BUT better suited normalisations possible (examples later)
- if full angular fit from experimental data possible then

1) $S^{(k)}_{1,2,3,4,7}$ and $A^{(k)}_{5,6,8,9}$ from $d^4(\Gamma + \bar{\Gamma})$ = flavour-untagged B samples

2) $A^{(k)}_{1,2,3,4,7}$ and $S^{(k)}_{5,6,8,9}$ from $d^4(\Gamma - \bar{\Gamma})$

CP-odd (i = 5,6,8,9) $\Rightarrow$ CP-asymmetries $\sim d^4(\Gamma + \bar{\Gamma})$

can be measured from untagged (equally mixed ???) B samples

??? requires knowledge of $\bar{B}/B$-fraction of untagged sample: LHCb vs SuperB

Observables - II

- decay rate $$\frac{d\Gamma}{dq^2} = \frac{3}{4}(2I_1^s + I_1^c) - \frac{1}{4}(2I_2^s + I_2^c), \qquad \frac{d\bar{\Gamma}}{dq^2} = \frac{d\Gamma}{dq^2}[I_i^{(k)} \to \bar{I}_i^{(k)}]$$
- rate CP-asymmetry

$$A_{\text{CP}} = \frac{d(\Gamma - \bar{\Gamma})}{dq^2} \Big/ \frac{d(\Gamma + \bar{\Gamma})}{dq^2} = \frac{3}{4}(2A_1^s + A_1^c) - \frac{1}{4}(2A_2^s + A_2^c)$$

- lepton forward-backward asymmetry

$$A_{\text{FB}} = \left[\int_0^1 - \int_{-1}^0\right] d\cos\theta_\ell \frac{d^2(\Gamma - \bar{\Gamma})}{dq^2\, d\cos\theta_\ell} \Big/ \frac{d(\Gamma + \bar{\Gamma})}{dq^2} = \frac{3}{8}(2S_6^s + S_6^c)$$

- lepton forward-backward CP-asymmetry

$$A_{\text{FB}}^{\text{CP}} = \left[\int_0^1 - \int_{-1}^0\right] d\cos\theta_\ell \frac{d^2(\Gamma + \bar{\Gamma})}{dq^2\, d\cos\theta_\ell} \Big/ \frac{d(\Gamma + \bar{\Gamma})}{dq^2} = \frac{3}{8}(2A_6^s + A_6^c)$$

- CP-ave. longitudinal and transverse K^* polarisation fractions

$$F_L = -S_2^c, \qquad F_T = 4S_2^s$$

Observables - III

- "transversity observables" (designed for low-q^2)

$$A_T^{(2)} = \frac{S_3}{2S_2^s}, \qquad A_T^{(3)} = \sqrt{\frac{4S_4^2 + S_7^2}{-2S_2^c\,(2S_2^s + S_3)}}, \qquad A_T^{(4)} = \sqrt{\frac{S_5^2 + 4S_8^2}{4S_4^2 + S_7^2}}$$

- lepton-flavour e, μ-non-universal (extend to $I_i^{(k)}$)

$$R_{K^*(X_s,\,K)} = \frac{d\Gamma[B \to K^*\,(X_s,\,K) + \bar{e}e]}{dq^2} \Big/ \frac{d\Gamma[B \to K^*\,(X_s,\,K) + \bar{\mu}\mu]}{dq^2}$$

- isospin asymmetry (extend to $I_i^{(k)}$ - only @ low-q^2, @ high-$q^2 \sim 1/m_b^3$)

$$A_I = \frac{(\tau_{B^+}/\tau_{B^0}) \times dBr[B^0 \to K^{*0}\bar{\ell}\ell] - dBr[B^+ \to K^{*+}\bar{\ell}\ell]}{(\tau_{B^+}/\tau_{B^0}) \times dBr[B^0 \to K^{*0}\bar{\ell}\ell] + dBr[B^+ \to K^{*+}\bar{\ell}\ell]}$$

- and others... $A_T^{(5)}$, A_{6s}^{V2s}, A_8^V, $H_T^{(1,2,3)}$...

likely that exp. results only in some q^2-integrated bins: $\langle \ldots \rangle = \int_{q^2_{min}}^{q^2_{max}} dq^2 \ldots$,
then use some (quasi-) single-diff. distributions in θ_ℓ, θ_{K^*}, ϕ

- $$\frac{d\langle\Gamma\rangle}{d\phi} = \frac{1}{2\pi}\left\{\langle\Gamma\rangle + \langle I_3\rangle\cos 2\phi + \langle I_9\rangle \sin 2\phi\right\}$$

- 2 bins in $\cos\theta_{K^*}$

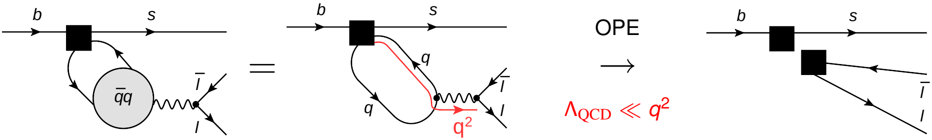
$$\frac{d\langle A_{\theta_{K^*}}\rangle}{d\phi} \equiv \int_{-1}^{1} d\cos\theta_l \left[\int_0^1 - \int_{-1}^0\right] d\cos\theta_{K^*}\, \frac{d^3\langle\Gamma\rangle}{d\cos\theta_{K^*}\, d\cos\theta_l\, d\phi}$$

$$= \frac{3}{16}\left\{\langle I_5\rangle\cos\phi + \langle I_7\rangle\sin\phi\right\}$$

- (2 bins in $\cos\theta_{K^*}$) + (2 bins in $\cos\theta_l$)

$$\frac{d\langle A_{\theta_{K^*},\theta_l}\rangle}{d\phi} \equiv \left[\int_0^1 - \int_{-1}^0\right] d\cos\theta_l\, \frac{d^2\langle A_{\theta_{K^*}}\rangle}{d\cos\theta_l\, d\phi} = \frac{1}{2\pi}\left\{\langle I_4\rangle\cos\phi + \langle I_8\rangle\sin\phi\right\}$$

Hard momentum transfer $(q^2 \sim M_B^2)$ through $(\bar{q}q) \to \bar{\ell}\ell$ allows local OPE



$$\mathcal{M}[\bar{B} \to \bar{K}^* + \bar{\ell}\ell] \sim \frac{8\pi^2}{q^2} i \int d^4x\, e^{iq\cdot x} \langle \bar{K}^* | T\{\mathcal{L}^{\rm eff}(0), j_\mu^{\rm em}(x)\} | \bar{B}\rangle \, [\bar{\ell}\gamma^\mu \ell]$$

$$= \left(\sum_a \mathcal{C}_{3a} \mathcal{Q}_{3a}^\mu + \sum_b \mathcal{C}_{5b} \mathcal{Q}_{5b}^\mu + \sum_c \mathcal{C}_{6c} \mathcal{Q}_{6c}^\mu + \mathcal{O}(dim > 6) \right) [\bar{\ell}\gamma_\mu \ell]$$

Buchalla/Isidori hep-ph/9801456, Grinstein/Pirjol hep-ph/0404250, Beylich/Buchalla/Feldmann arXiv:1101.5118

Leading $dim = 3$ operators: $\langle \bar{K}^* | \mathcal{Q}_{3,a} | \bar{B}\rangle \sim$ usual $B \to K^*$ form factors $V, A_{0,1,2}, T_{1,2,3}$

$$\mathcal{Q}_{3,1}^\mu = \left(g^{\mu\nu} - \frac{q^\mu q^\nu}{q^2} \right) [\bar{s}\,\gamma_\nu (1-\gamma_5)\, b] \qquad \to \qquad C_9 \to C_9^{\rm eff}, \qquad (V, A_{0,1,2})$$

$$\mathcal{Q}_{3,2}^\mu = \frac{i m_b}{q^2} q_\nu \, [\bar{s}\,\sigma_{\nu\mu} (1+\gamma_5)\, b] \qquad \to \qquad C_7 \to C_7^{\rm eff}, \qquad (T_{1,2,3})$$

HIGH-q^2: OPE – II

$dim = 3$ α_s matching corrections are also known

$m_s \neq 0$ 2 additional $dim = 3$ operators, suppressed with $\alpha_s m_s/m_b \sim 0.5\,\%$, NO new form factors

$dim = 4$ absent

$dim = 5$ suppressed by $(\Lambda_{\mathrm{QCD}}/m_b)^2 \sim 2\,\%$, explicite estimate @ $q^2 = 15\ \mathrm{GeV}^2$: $< 1\%$ [Beylich/Buchalla/Feldmann arXiv:1101.5118]

$dim = 6$ suppressed by $(\Lambda_{\mathrm{QCD}}/m_b)^3 \sim 0.2\,\%$ and small QCD-penguin's: $C_{3,4,5,6}$ spectator quark effects: from weak annihilation

BEYOND OPE duality violating effects [Beylich/Buchalla/Feldmann arXiv:1101.5118]

- based on Shifman model for c-quark correlator + fit to recent BES data
- $\pm 2\,\%$ for integrated rate $q^2 > 15\ \mathrm{GeV}^2$

$\Rightarrow$ OPE of exclusive $\bar{B} \to \bar{K}^*(\bar{K}) + \bar{\ell}\ell$ predicts small sub-leading contributions !!!

BUT, still missing $B \to K^*$ form factors @ high-q^2
for predictions of angular observables $I_i^{(k)}$

ANY other effects to consider ???

HIGH-q^2: OPE + HQET – I

Framework developed by Grinstein/Pirjol hep-ph/0404250

1) OPE in $\Lambda_{\rm QCD}/Q$ with $Q = \{m_b, \sqrt{q^2}\}$ + matching on HQET + expansion in m_c

$$\mathcal{M}[\bar{B} \to \bar{K}^* + \bar{\ell}\ell] \sim \frac{8\pi}{q^2} \sum_{i=1}^{6} C_i(\mu)\, \mathcal{T}_\alpha^{(i)}(q^2, \mu)\, [\bar{\ell}\gamma^\alpha \ell]$$

$$\mathcal{T}_\alpha^{(i)}(q^2, \mu) = i \int d^4x\, e^{iq\cdot x} \langle \bar{K}^* | T\{\mathcal{O}_i(0), j_\alpha^{\rm em}(x)\} | \bar{B}\rangle$$

$$= \sum_{k \geqslant -2} \sum_j C_{i,j}^{(k)} \langle \mathcal{Q}_{j,\alpha}^{(k)} \rangle$$

$\mathcal{Q}_{j,\alpha}^{(k)}$	power	$\mathcal{O}(\alpha_s)$
$\mathcal{Q}_{1,2}^{(-2)}$	1	$\alpha_s^0(Q)$
$\mathcal{Q}_{1-5}^{(-1)}$	$\Lambda_{\rm QCD}/Q$	$\alpha_s^1(Q)$
$\mathcal{Q}_{1,2}^{(0)}$	m_c^2/Q^2	$\alpha_s^0(Q)$
$\mathcal{Q}_{j>3}^{(0)}$	${\Lambda_{\rm QCD}}^2/Q^2$	$\alpha_s^0(Q)$
$\mathcal{Q}_i^{(2)}$	m_c^4/Q^4	$\alpha_s^0(Q)$

included,
unc. estimate by naive pwr cont.

2) HQET FF-relations at sub-leading order + α_s corrections in leading order

$$T_1(q^2) = \kappa\, V(q^2), \qquad T_2(q^2) = \kappa\, A_1(q^2), \qquad T_3(q^2) = \kappa\, A_2(q^2)\frac{M_B^2}{q^2},$$

$$\kappa = \left(1 + \frac{2D_0^{(v)}(\mu)}{C_0^{(v)}(\mu)}\right) \frac{m_b(\mu)}{M_B}$$

can express everything in terms of QCD FF's $V, A_{1,2}$ @ $\mathcal{O}(\alpha_s \Lambda_{\rm QCD}/Q)$!!!

HIGH-q^2 – AMPLITUDE STRUCTURE

TRANSVERSITY AMPLITUDES $A_i^{L,R}(\bar{B} \to \bar{K}^* \bar{\ell}\ell)$

$$A_\perp^{L,R} = +\left[C^{L,R} + \tilde{r}_a\right] f_\perp\,, \qquad A_\parallel^{L,R} = -\left[C^{L,R} + \tilde{r}_b\right] f_\parallel\,,$$

$$A_0^{L,R} = -C^{L,R} f_0 - N M_B \frac{(1-\hat{s}-\hat{M}_{K^*}^2)(1+\hat{M}_{K^*})^2 \tilde{r}_b A_1 - \hat{\lambda}\,\tilde{r}_c A_2}{2\,\hat{M}_{K^*}(1+\hat{M}_{K^*})\sqrt{\hat{s}}}$$

$\Rightarrow$ Universal short-distance coefficients: $C^{L,R} = C_9^{\rm eff} + \kappa \frac{2 m_b M_B}{q^2} C_7^{\rm eff} \mp C_{10}$

(SM: $C_9 \sim +4$, $C_{10} \sim -4$, $C_7 \sim -0.3$)

known structure of sub-leading corrections (Grinstein/Pirjol hep-ph/0404250)

$$\tilde{r}_i \sim \pm \frac{\Lambda_{\rm QCD}}{m_b} \left(C_7^{\rm eff} + \alpha_s(\mu) e^{i\delta_i}\right)\,, \qquad i = a, b, c$$

Non-PT FF's ("helicity FF's" Bharucha/Feldmann/Wick arXiv:1004.3249)

$$f_\perp = \frac{\sqrt{2\hat{\lambda}}}{1+\hat{M}_{K^*}} V, \qquad f_\parallel = \sqrt{2}\,(1+\hat{M}_{K^*})\,A_1, \qquad f_0 = \frac{(1-\hat{s}-\hat{M}_{K^*}^2)(1+\hat{M}_{K^*})^2 A_1 - \hat{\lambda}\,A_2}{2\,\hat{M}_{K^*}(1+\hat{M}_{K^*})\sqrt{\hat{s}}}$$

HIGH-q^2 – SM OPERATOR BASIS

ANGULAR OBSERVABLES ($m_\ell = 0$)

$$(2\, I_2^s + I_3) = 2\, \rho_1\, f_\perp^2, \qquad -I_2^c = 2\, \rho_1\, f_0^2, \qquad I_5/\sqrt{2} = 4\, \rho_2\, f_0 f_\perp,$$

$$(2\, I_2^s - I_3) = 2\, \rho_1\, f_\parallel^2, \qquad \sqrt{2}\, I_4 = 2\, \rho_1\, f_0 f_\parallel, \qquad I_6^s/2 = 4\, \rho_2\, f_\parallel f_\perp,$$

$$I_7 = I_8 = I_9 = 0, \qquad (I_6^c = 0)$$

$$\rho_1 = \frac{1}{2}\left(|C^R|^2 + |C^L|^2\right) = \left|C_9^{\rm eff} + \kappa \frac{2 m_b^2}{q^2} C_7^{\rm eff}\right|^2 + |C_{10}|^2 = N_{\rm eff}\ (\text{Grinstein/Pirjol}),$$

$$\rho_2 = \frac{1}{4}\left(|C^R|^2 - |C^L|^2\right) = \mathrm{Re}\left[\left(C_9^{\rm eff} + \kappa \frac{2 m_b^2}{q^2} C_7^{\rm eff}\right) C_{10}^*\right]$$

ρ_1 and ρ_2 are largely μ-scale independent (NNLL)

$$\frac{d\Gamma}{dq^2} = 2\, \rho_1 \times (f_0^2 + f_\perp^2 + f_\parallel^2), \qquad A_{\rm FB} = 3\, \frac{\rho_2}{\rho_1} \times \frac{f_\perp f_\parallel}{(f_0^2 + f_\perp^2 + f_\parallel^2)},$$

$$F_{\rm L} = \frac{f_0^2}{f_0^2 + f_\perp^2 + f_\parallel^2}, \qquad A_T^{(2)} = \frac{f_\perp^2 - f_\parallel^2}{f_\perp^2 + f_\parallel^2}, \qquad A_T^{(3)} = \frac{f_\parallel}{f_\perp}, \qquad A_T^{(4)} = 2\, \frac{\rho_2}{\rho_1} \times \frac{f_\perp}{f_\parallel}$$

HIGH-q^2 – "LONG-DISTANCE FREE"

FF-FREE RATIOS !!! TEST SD FLAVOUR COUPLINGS VERSUS EXP. DATA + OPE

$$H_T^{(1)} = \frac{\sqrt{2} I_4}{\sqrt{-I_2^c \left(2 I_2^s - I_3\right)}} = 1$$

$$H_T^{(2)} = \frac{I_5}{\sqrt{-2 I_2^c \left(2 I_2^s + I_3\right)}} = 2\,\frac{\rho_2}{\rho_1}, \qquad H_T^{(3)} = \frac{I_6}{2\sqrt{(2 I_2^s)^2 - I_3^2}} = 2\,\frac{\rho_2}{\rho_1}$$

SM predictions integrated $q^2 \in [14,\ 19.2]$ GeV^2 (CB/Hiller/van Dyk arXiv:1006.5013)

$$\langle H_T^{(1)} \rangle = +0.997 \pm 0.002\Big|_{\text{FF}} {}^{+0.000}_{-0.001}\Big|_{\text{IWR}},$$

$$\langle H_T^{(2)} \rangle = -0.972\, {}^{+0.004}_{-0.003}\Big|_{\text{FF}} \pm 0.001\Big|_{\text{SL}} {}^{+0.008}_{-0.005}\Big|_{\text{IWR}} {}^{+0.003}_{-0.004}\Big|_{\text{SD}},$$

$$\langle H_T^{(3)} \rangle = -0.958 \pm 0.001\Big|_{\text{SL}} {}^{+0.008}_{-0.006}\Big|_{\text{IWR}} {}^{+0.003}_{-0.004}\Big|_{\text{SD}}$$

⇒ Assuming validity of LCSR extrapolation Ball/Zwicky [hep-ph/0412079] of $V, A_{1,2}(q^2)$ to $q^2 > 14$ GeV^2 based form factor parametrisation using dipole formula

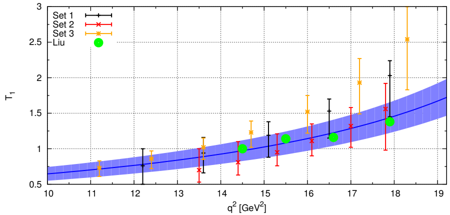
⇒ $\langle \ldots \rangle$ = q^2-integration performed in analogy to experimental measurement for each $I_i^{(k)}$ before taking ratio and $\sqrt{\ldots}$

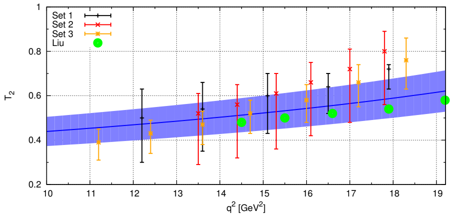
HIGH-q^2 – "SHORT-DISTANCE FREE"

SHORT-DISTANCE-FREE RATIOS !!! TEST LATTICE VERSUS EXP. DATA + OPE

$$\frac{f_0}{f_\parallel} = \frac{\sqrt{2} I_5}{I_6} = \frac{-I_2^c}{\sqrt{2} I_4} = \frac{\sqrt{2} I_4}{2 I_2^s - I_3} = \sqrt{\frac{-I_2^c}{2 I_2^s - I_3}},$$

$$\frac{f_\perp}{f_\parallel} = \sqrt{\frac{2 I_2^s + I_3}{2 I_2^s - I_3}} = \frac{\sqrt{-I_2^c \left(2 I_2^s + I_3\right)}}{\sqrt{2} I_4}, \qquad \frac{f_0}{f_\perp} = \sqrt{\frac{-I_2^c}{2 I_2^s + I_3}}$$



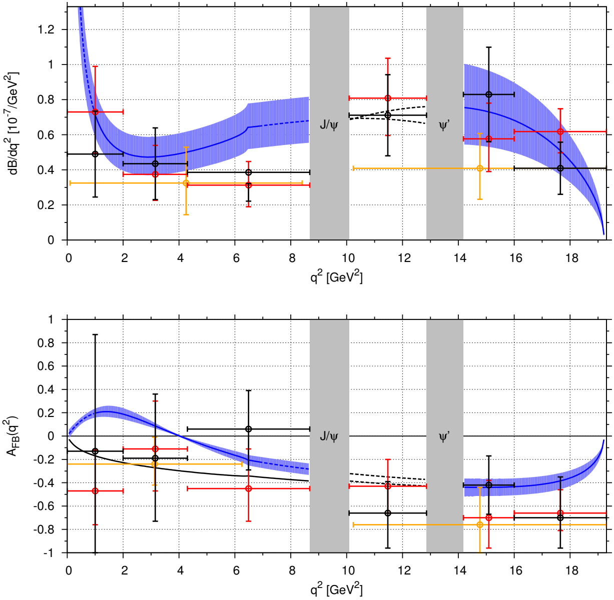


LCSR extrapolation (Ball/Zwicky hep-ph/0412079) of $T_1(q^2)$ and $T_2(q^2)$ to high-q^2 versus quenched Lattice (3 data sets from Becirevic/Lubicz/Mescia hep-ph/0611295)

new unquenched Lattice results to come → Liu/Meinel/Hart/Horgan/Müller/Wingate arXiv:0911.2370, arXiv:1101.2726 no final uncertainty estimate yet

NO lattice results yet for $B \to K^*$ FF's @ high-q^2: V, $A_{0,1,2}$, T_3 !!!

HIGH-q^2 – Br, A_{fb}



Br and A_{FB}

SM prediction + unc.
@ low- and high-q^2

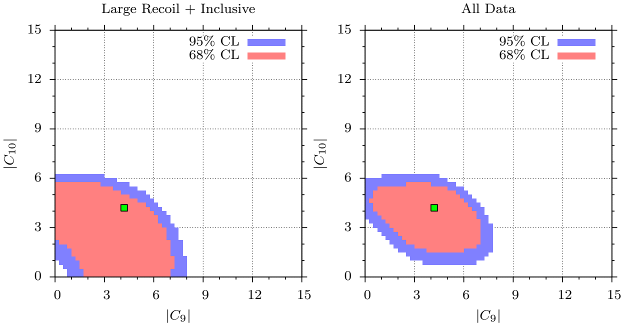
Data points from

[Babar '08]

[Belle '09]

[CDF '10]

“Global” Fit of C_9 and C_{10} – complex



CB/Hiller/van Dyk arXiv:1105.0376

Scan resolution

$|C_7| \in [.30, .35], \quad \Delta|C_7| = .01$

$|C_{9,10}| \in [0, 15], \quad \Delta|C_{9,10}| = 0.25$

$\phi_7 \in [0, 2\pi), \quad \Delta\phi_7 = \pi/16$

$\phi_{9,10} \in [0, 2\pi), \quad \Delta\phi_{9,10} = \pi/16$

SM = green square

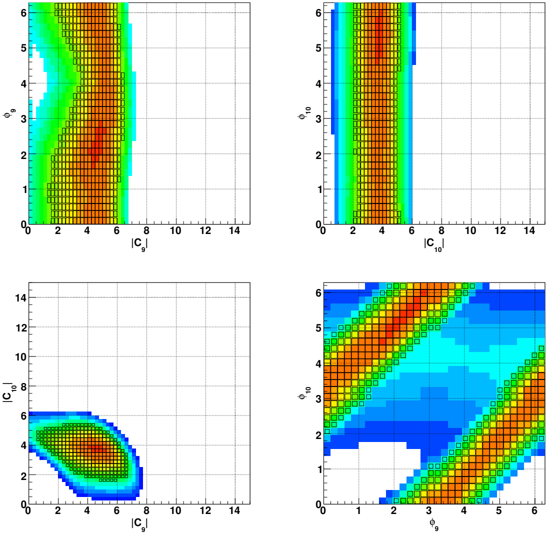
- $B \to X_s \bar{\ell}\ell$ Babar/Belle data: Br in q^2-bin: $[1, 6]$ GeV^2
- $B \to K^* \bar{\ell}\ell$ Belle/CDF data: Br, $A_{\rm FB}$, F_L in q^2-bin: $[1, 6]$ GeV^2
  Br, $A_{\rm FB}$ in q^2-bins: $[14.2, 16]$ GeV^2 and $[> 16]$ GeV^2

Determining 68 (95) % CL in 6D pmr-space $|C_{7,9,10}|$ and $\phi_{7,9,10}$ $\to$ projection on $|C_9| - |C_{10}|$

$\Rightarrow$ without high-q^2 data [left] and with [right] $\to$ important impact,
BUT form factors from lattice very desirable !!!

$\Rightarrow Br(B_s \to \bar{\mu}\mu) < 1 \cdot 10^{-8}$ @ 95 % CL

Model-indep. fit of complex $C_{9,10}$ ($C_9^{\rm SM} = 4.2,\ C_{10}^{\rm SM} = -4.2$)



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

- Br and $A_{\rm FB}$ in q^2-bins

  $[1, 6]$ GeV^2
  $[14.2, 16]$ GeV^2
  $[> 16]$ GeV^2

- F_L in $q^2 \in [1, 6]$ GeV^2

$B \to X_s \bar{\ell}\ell$

- Br in $[1, 6]$ GeV^2

$B \to K \bar{\ell}\ell$

- Br in $[1, 6]$, $[14.2, 16]$, $[> 16]$ GeV^2

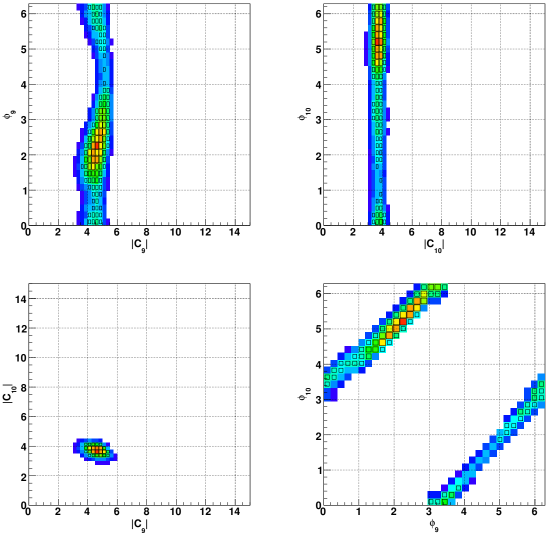
margnialised profile likelihood 95 % (68 % box) CL regions

- ▶ $|C_7| = |C_7^{\rm SM}|$
- ▶ $|C_{9,10}| \in [0, 15]$
- ▶ $\phi_{7,9,10} \in [0, 2\pi)$

preliminary
Beaujean/CB/van Dyk/Wacker

FIT $C_{9,10}$ – COMPLEX – FUTURE?

For fun: keep exp. central values, divide all exp. errors by 5



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

- Br and $A_{\rm FB}$ in q^2-bins

  $[1, 6]$ GeV^2
  $[14.2, 16]$ GeV^2
  $[> 16]$ GeV^2

- F_L in $q^2 \in [1, 6]$ GeV^2

$B \to X_s \bar{\ell}\ell$

- Br in $[1, 6]$ GeV^2

$B \to K \bar{\ell}\ell$

- Br in $[1, 6]$, $[14.2, 16]$, $[> 16]$ GeV^2

margnialised profile likelihood
95 % (68 % box) CL regions

- ▶ $|C_7| = |C_7^{\rm SM}|$
- ▶ $|C_{9,10}| \in [0, 15]$
- ▶ $\phi_{7,9,10} \in [0, 2\pi)$

preliminary
Beaujean/CB/van Dyk/Wacker

CP-asymmetries @ high-q^2

FF-free CP-asymmetries: SM operator basis [CB/Hiller/van Dyk arXiv:1105.0376]

$$a_{\mathrm{CP}}^{(1)} = \frac{\rho_1 - \bar{\rho}_1}{\rho_1 + \bar{\rho}_1}\,, \qquad a_{\mathrm{CP}}^{(2)} = \frac{\frac{\rho_2}{\rho_1} - \frac{\bar{\rho}_2}{\bar{\rho}_1}}{\frac{\rho_2}{\rho_1} + \frac{\bar{\rho}_2}{\bar{\rho}_1}}\,, \qquad a_{\mathrm{CP}}^{(3)} = 2\,\frac{\rho_2 - \bar{\rho}_2}{\rho_1 + \bar{\rho}_1}$$

- NLO QCD corrections large
- still, theoretical uncertainties large: dominated by renorm. scale μ_b
- a_{CP}^{mix} in $B_s \to \phi(\to K^+K^-) + \bar{\ell}\ell$

Including BSM-operators: SM' = $O_{7',9',10'}$ [work in progress CB/Hiller/van Dyk]

$$A^{L,R}_{0,\|} = -C^{L,R}_{-} f_{0,\|}, \qquad A^{L,R}_{\perp} = +C^{L,R}_{+} f_{\perp}$$

with universal coefficients $C^{L,R} \to C^{L,R}_{\pm}$

$$C^{L,R}_{-} = \left[(C_9^{\rm eff} - C_{9'}^{\rm eff}) + \kappa \frac{2m_b^2}{q^2} (C_7^{\rm eff} - C_{7'}^{\rm eff}) \right] \mp (C_{10} - C_{10'}),$$

$$C^{L,R}_{+} = \left[(C_9^{\rm eff} + C_{9'}^{\rm eff}) + \kappa \frac{2m_b^2}{q^2} (C_7^{\rm eff} + C_{7'}^{\rm eff}) \right] \mp (C_{10} + C_{10'})$$

Now the angular observables $I_i^{(k)}$ ($m_\ell = 0$) read

$$\frac{4}{3}(2I_2^s + I_3) = 2\,\rho_1^+ f_\perp^2, \qquad \frac{4\sqrt{2}}{3} I_4 = 2\,\rho_1^- f_0 f_\|, \qquad I_7 = 0,$$

$$\frac{4}{3}(2I_2^s - I_3) = 2\,\rho_1^- f_\|^2, \qquad \frac{2\sqrt{2}}{3} I_5 = 4\,{\rm Re}(\rho_2) f_0 f_\perp, \qquad \frac{4\sqrt{2}}{3} I_8 = 4\,{\rm Im}(\rho_2) f_0 f_\perp,$$

$$-\frac{4}{3} I_2^c = 2\,\rho_1^- f_0^2, \qquad \frac{2}{3} I_6 = 4\,{\rm Re}(\rho_2) f_\| f_\perp, \qquad -\frac{4}{3} I_9 = 4\,{\rm Im}(\rho_2) f_\| f_\perp$$

where ρ_1 and ρ_2 have to be generalised

$$\rho_1^\pm = \frac{1}{2}\left(|C^R_\pm|^2 + |C^L_\pm|^2 \right), \qquad \rho_2 = \frac{1}{4}\left(C^R_+ C^{R*}_- - C^L_- C^{L*}_+ \right)$$

BSM OPERATORS @ HIGH-q^2 – II

Including BSM-operators [work in progress CB/Hiller/van Dyk]

- extension to $\rho_1 \to \rho_1^\pm$
- still have $H_T^{(1)} = 1$
- $I_7 = 0$, but $I_{8,9} \neq 0$
- generalisation: $H_T^{(2)} = H_T^{(3)} = 2\,\frac{\mathrm{Re}(\rho_2)}{\sqrt{\rho_1^- \cdot \rho_1^+}}$
- 2 new FF-free ratios

$$H_T^{(4)} = \frac{\sqrt{2} I_8}{\sqrt{-I_2^c\,(2I_2^s + I_3)}} = 2\,\frac{\mathrm{Im}(\rho_2)}{\sqrt{\rho_1^- \cdot \rho_1^+}}, \qquad H_T^{(5)} = \frac{-I_9}{\sqrt{(2I_2^s)^2 - I_3^2}} = 2\,\frac{\mathrm{Im}(\rho_2)}{\sqrt{\rho_1^- \cdot \rho_1^+}}.$$

- $a_{\mathrm{CP}}^{(1)} \to a_{\mathrm{CP}}^{(1,\pm)}$ and $a_{\mathrm{CP}}^{(2)} \to a_{\mathrm{CP}}^{(2,\pm)}$
- generalisation of $a_{\mathrm{CP}}^{(3)}$ and additional

$$a_{\mathrm{CP}}^{(3)} = 2\,\frac{\mathrm{Re}(\rho_2 - \bar{\rho}_2)}{\sqrt{(\rho_1^+ - \bar{\rho}_1^+)\cdot(\rho_1^- - \bar{\rho}_1^-)}}, \qquad a_{\mathrm{CP}}^{(4)} = 2\,\frac{\mathrm{Im}(\rho_2 - \bar{\rho}_2)}{\sqrt{(\rho_1^+ - \bar{\rho}_1^+)\cdot(\rho_1^- - \bar{\rho}_1^-)}}$$

- less “short-distance free” ratios, only $f_0/f_{\|}$

$$B \to P + \bar{\ell}\ell$$

$B \to K + \bar{\ell}\ell$ @ HIGH-q^2 - I

FF RELATION (ISGUR/WISE) IN HEAVY QUARK LIMIT

$$f_T(q^2, \mu) = \frac{(M_B + M_K) M_B}{q^2} \kappa(\mu) f_+(q^2) + \mathcal{O}\left(\frac{\Lambda_{\rm QCD}}{M_B}\right)$$

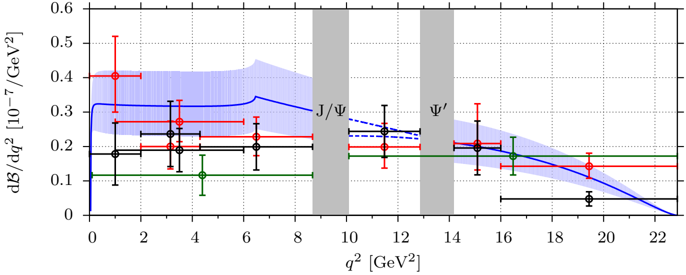
Grinstein/Pirjol hep-ph/0201298, hep-ph/0404250, $\kappa = 1 + \mathcal{O}(\alpha_s)$: known QCD matching correction

MATRIX ELEMENT @ HIGH-q^2

$$\mathcal{M}[\bar{B} \to \bar{K}\bar{\ell}\ell] \propto G_F \alpha_e V_{tb} V_{ts}^* f_+(q^2) \left(F_V\, p_B^\mu [\bar{\ell}\gamma_\mu \ell] + F_A\, p_B^\mu [\bar{\ell}\gamma_\mu \gamma_5 \ell] + F_P\, m_\ell [\bar{\ell}\gamma_5 \ell] \right)$$

$$F_A = C_{10}, \qquad F_V = C_9^{\rm eff} + \kappa \frac{2 m_b^2}{q^2} C_7^{\rm eff}, \qquad F_P = C_{10}\left[\frac{(M_B^2 - M_K^2)}{q^2}\left(\frac{f_0}{f_+} - 1\right) - 1\right]$$

$B \to K + \bar{\ell}\ell$ @ HIGH-q^2 – II



preliminary CB/Hiller/van Dyk/Wacker

for $\ell = e, \mu$ ($m_\ell = 0$)

$$\frac{d\Gamma}{dq^2} = \frac{\Gamma_0}{4} (\sqrt{\lambda})^3 \rho_1 f_+^2, \qquad A_{\rm CP}(q^2) = \frac{d\Gamma/dq^2 - d\bar{\Gamma}/dq^2}{d\Gamma/dq^2 + d\bar{\Gamma}/dq^2} = \frac{\rho_1 - \bar{\rho}_1}{\rho_1 + \bar{\rho}_1}$$

$\Rightarrow$ rate CP-asymmetry is also "long-distance-free" and

$$A_{\rm CP}[B \to K\bar{\ell}\ell] = a_{\rm CP}^{(1)}[B \to K^*\bar{\ell}\ell]$$

see also Bartsch/Beylich/Buchalla/Gao arXiv:0909.1512: $Br(B \to K + \bar{\nu}\nu)/Br(B \to K + \bar{\ell}\ell)$

Conclusion - I

- rich phenomenology in angular analysis of $B \to V_{on-shell}(\to P_1 P_2) + \bar{\ell}\ell$ to test flavour short-distance couplings – analogously $B_s \to \phi(\to K^+K^-) + \bar{\ell}\ell$
- low-q^2 and high-q^2 regions in $b \to s + \bar{\ell}\ell$ accesible via power exp's (QCDF, SCET, OPE + HQET) $\to$ reveal symmetries of QCD dynamics
- reducing Non-PT uncertainties by suiteable ratios of observables guided by power exp's $\to$ allowing for quite precise theory predictions for exclusive decays
- low-q^2 theoretically well understood (even $(\bar{c}c)$-resonances can be estimated) $\to$ many interesting tests, waiting for data
- high-q^2:
  - $(\bar{c}c)$-resonances seem under control, violation of $H_T^{(1)} = 1$ can be tested
  - "long-distance free" ratios $H_T^{(2,3)}$ to test SM
  - "short-distance free" ratios to test q^2-dep. of FF-ratios directly with lattice
  - need FF input from Lattice $\to$ required to exploit exp. data dBr/dq^2

Conclusion – II

Other phenomenological topics

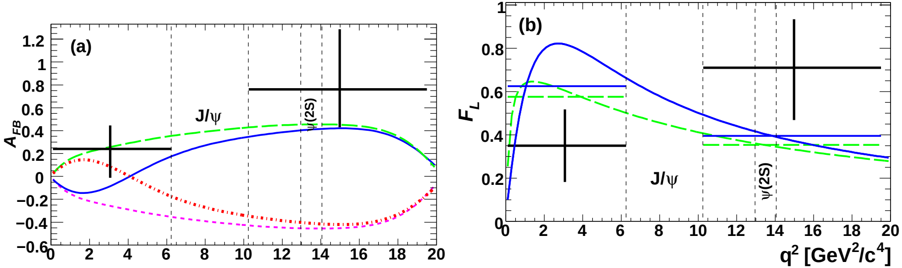
- separate measurement of $\ell = e$ and $\ell = \mu$: investigate ratios of $I_i^{(k)}(\ell = e)/I_i^{(k)}(\ell = \mu)$ in analogy to R_{K^*} @ low- and high-q^2 $\rightarrow$ ℓ-flavour non-universal effects
- combination of $B \rightarrow K\bar{\ell}\ell$ and $B \rightarrow K^*\bar{\ell}\ell$ – work in progress CB/Hiller/van Dyk/Wacker
- measurement of $B \rightarrow (K, K^*) + \bar{\tau}\tau$ feaseable ???
  $\rightarrow$ interesting for BSM scenarios with scalar and pseudo-scalar operators
- combined measurement of $B \rightarrow K + \bar{\nu}\nu$ and $B \rightarrow K + \bar{\ell}\ell$ – Bartsch/Beylich/Buchalla/Gao arXiv:09091512
- $B \rightarrow X_s\bar{\ell}\ell$ @ high-q^2

EOS = new Flavour tool @ TU Dortmund by Danny van Dyk et al.
http://project.het.physik.tu-dortmund.de/eos/

$\Rightarrow$ Danny van Dyk presentation tomorrow

Backup slides

Analysis of 384 M $B\bar{B}$ pairs → search all channels $B^{+,0}$, $K^{(*),+,-}$ and $\ell = e,\ \mu$



- 2 bins: low-$q^2 \in [0.1 - 6.25]$ GeV^2 and high-$q^2 > 10.24$ GeV^2

  $$\Rightarrow (27 \pm 6) + (37 \pm 10) = 64 \text{ events}$$

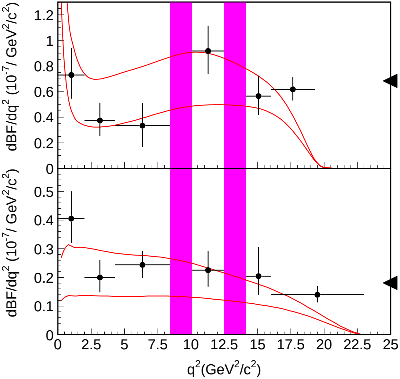
- veto of J/ψ and ψ' regions: background $B \to K^*(\bar{c}c) \to K^*\bar{\ell}\ell$
- angular analysis in each q^2-bin in θ_ℓ and θ_{K^*} ⇒ fit F_L and $A_{\rm FB}$

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_{K^*}} = \frac{3}{2}F_L\cos^2\theta_{K^*} + (1 - F_L)(1 - \cos^2\theta_{K^*}),$$

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_\ell} = \frac{3}{4}F_L(1 - \cos^2\theta_\ell) + \frac{3}{8}(1 - F_L)(1 + \cos^2\theta_\ell) + A_{\rm FB}\cos\theta_\ell$$

Belle [arXiv:0904.0770]

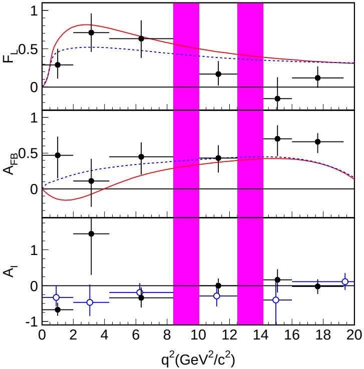
Analysis of 657 M $B\bar{B}$ pairs = 605 fb^{-1} $\to$ search all channels $B^{+,0}$, $K^{(*),+,-}$ and $\ell = e, \mu$



◀ $B \to K^* \bar{\ell}\ell$

red = SM

◀ $B \to K\bar{\ell}\ell$

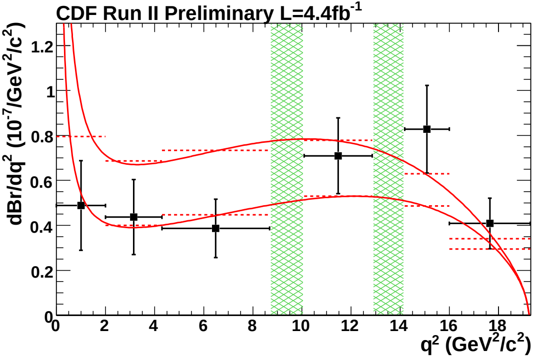


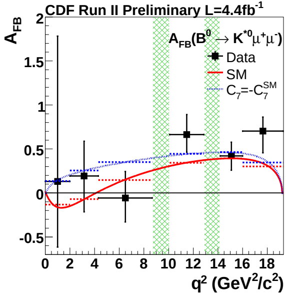
- 6 bins $\Rightarrow$ 247 events (121 @ $q^2 > 14$ GeV^2)
- angular analysis in each q^2-bin in θ_ℓ and θ_{K^*} $\Rightarrow$ fit F_L and $A_{\rm FB}$
- all-q^2 extrapolated results:

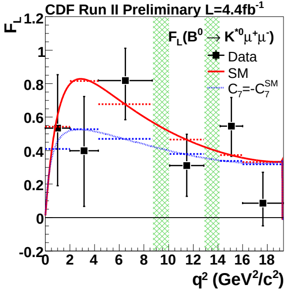
$$Br = (10.7^{+1.1}_{-1.0} \pm 0.09) \times 10^{-7}, \qquad A_{\rm CP} = -0.10 \pm 0.10 \pm 0.01,$$

$$R_{K^*} = 0.83 \pm 0.17 \pm 0.08 \text{ (SM} = 0.75), \qquad A_I = -0.29^{+0.16}_{-0.16} \pm 0.09 \; (q^2 < 8.68 \text{ GeV}^2)$$

- analysis of 4.4 fb^{-1} (CDF Run II) $\Rightarrow$ only $B^0 \to K^{*0}\bar{\mu}\mu$
- discovery of $B_s \to \phi\bar{\mu}\mu$ 6.3 σ (27 $\pm$ 6) events
- 101 events (42 @ $q^2 > 14$ GeV^2) - Belle q^2-binning







EXPERIMENTAL PROSPECTS – I

Improvement of current experiments

BABAR + BELLE analysis of final data set in progress

CDF $(2-3)\times$ CDF data set through 2011 from 4.4 fb^{-1} $\to$ $(9-13)$ fb^{-1}
(more data, improved analysis and final states)

LHCb prospects for 2.0 fb^{-1} (= by the end of 2012 ???)

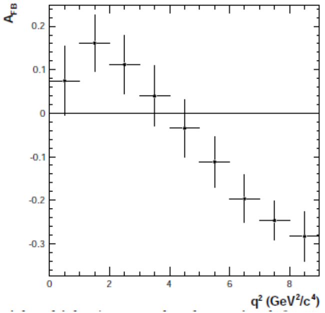
$\ell = \mu$ expected events after selection [arXiv:0912.4179]

a) cut-based: (4200^{+1100}_{-1000}) events
$(B/S = 0.05 \pm 0.04$ and $S/\sqrt{S+B} = 63^{+9}_{-8})$

b) multivariate: (6200^{+1700}_{-1500}) events
$(B/S = 0.25 \pm 0.08$ and $S/\sqrt{S+B} = 71^{+11}_{-10})$

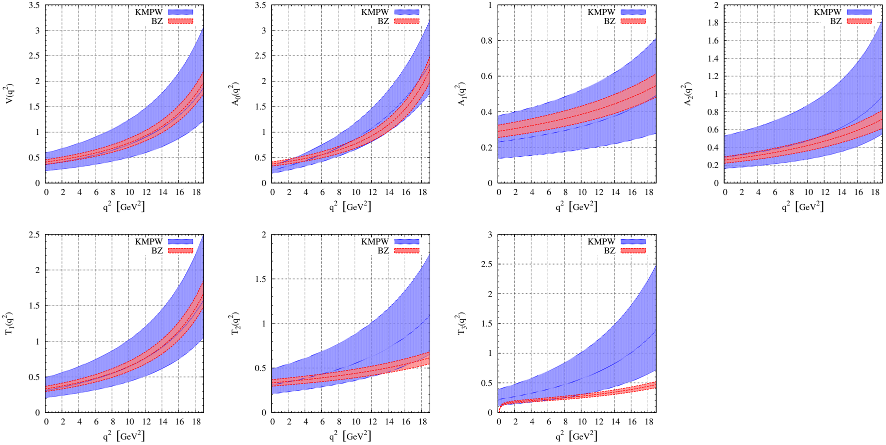
$\to$ currently: (Babar + Belle + CDF) $\approx$ 410 events

q_0^2 of $A_{\rm FB}$ expected with stat. unc. of ± 0.5 GeV^2
(B factory uncertainty expected with 0.3 fb^{-1})



$\ell = e$ $\sim (200-250)$ events per 2.0 fb^{-1} with $S/B \sim 1$
[LHCb-PUB-2009-008]

EXTRAPOLATION OF LCSR $B \to K^*$ FF'S TO HIGH-q^2



BZ = Ball/Zwicky hep-ph/0412079
KMPW = Khodjamirian/Mannel/Pivovarov/Wang arXiv:1006.4945

numerically most important for $B \to K^* \bar{\ell}\ell$: V and A_1