ANGULAR ANALYSIS OF $B \to V(\to P_1 P_2) + \bar{\ell}\ell$ DECAYS

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OUTLINE

1) Effective theory (EFT) of $\Delta B = 1$ FCNC decays
   - A) In the Standard Model (SM)
   - B) Beyond the SM (BSM)

2) $B \to V_{on-shell} (\to P_1 P_2) + \bar{\ell}\ell$
   - A) Kinematics and observables in angular distribution
   - B) Experimental results and prospects
   - C) $\bar{c}c$-backgrounds and q^2-regions
   - D) Low-q^2 phenomenology
   - E) High-q^2 phenomenology

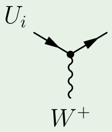
EFT of $\Delta B = 1$ decays in SM and beyond

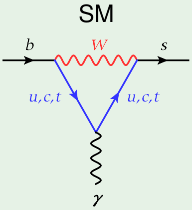
FCNC DECAYS IN THE SM

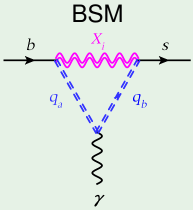
FLAVOUR CHANGING NEUTRAL CURRENT: $D_i \to D_j$ (AND $U_i \to U_j$)

$U_i = \{u, c, t\}$, $Q_U = +2/3$

$D_j = \{d, s, b\}$, $Q_D = -1/3$

$\mathcal{L}_{\mathrm{SM-FC}} \sim$  $\sim V_{ij}^{\mathrm{CKM}}$



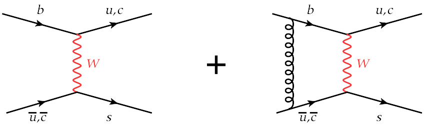


FCNC processes in the SM are

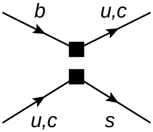
- quantum fluctuations = loop-supressed
  $\to$ no suppression of BSM contributions wrt SM
  $\to$ indirect search for BSM signals
- strong scale hierarchy among external and internal scales in FCNC B decays
  $\Longrightarrow \quad (m_b \approx 5\,\mathrm{GeV}) \ll (M_W \approx 80\,\mathrm{GeV})$

$\Delta B = 1$ EFT IN THE SM (FOR $b \to s$)

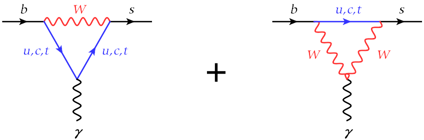
1) decoupling (OPE) of heavy particles ($W, Z, t, \ldots$) @ EW scale: $\mu_{EW} \gtrsim M_W$
   $\to$ factorisation into short-distance: C_i and long-distance: $\mathcal{O}_i$
2) RG-running to lower scale: $\mu_b \sim m_b$ $\to$ resums large log's: $[\alpha_s \ln(\mu_b/\mu_{EW})]^n$



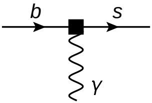
$\longrightarrow$ $C^0_{1,2} + \frac{\alpha_s}{4\pi} C^{(1)}_{1,2} \times$

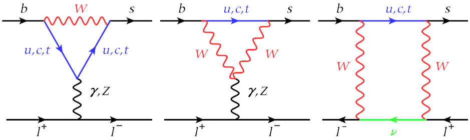


Most relevant for $b \to s + \bar{\ell}\ell$

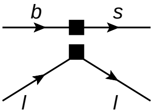


$\longrightarrow$ $C^{\gamma}_7 \times$





$\longrightarrow$ $C^{\ell\ell}_{9,10} \times$



SM OPERATOR LIST

. . . USING CKM UNITARITY

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

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

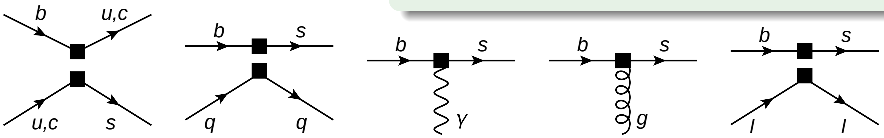
$\mathcal{O}_{1,2}^{u,c}$ = curr.-curr.: $b \to s\,\bar{u}u$, $b \to s\,\bar{c}c$

CP-violation in the SM is tiny

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

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

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



GENERAL APPROACH BEYOND SM ...

MODEL-DEP. 1) decoupl. 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 $\rightarrow \ldots$

... beyond the SM:

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

$$\mathcal{L}_{\rm EFT}(\mu_b) = \mathcal{L}_{\rm QED \times QCD}(u, d, s, c, b,\ e, \mu, \tau,\ ???)$$

$$+ \frac{4 G_F}{\sqrt{2}} V_{\rm CKM} \sum_{\rm SM} (C_i + \Delta C_i) \mathcal{O}_i + \sum_{\rm NP} C_j \mathcal{O}_j(???)$$

BEYOND THE SM OPERATOR LIST

frequently considered in model-(in)dependent searches

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

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

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

$$\mathcal{O}_{T,T5}^{\ell\ell} = \frac{\alpha_e}{4\pi} [\bar{s}\,\sigma_{\mu\nu}\, b][\bar{\ell}\,\sigma^{\mu\nu}(1, \gamma_5)\,\ell],$$

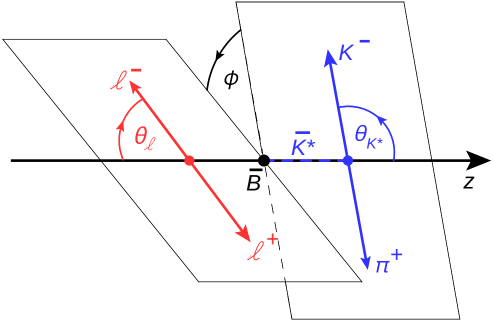
- new Dirac-structures beyond SM: right-handed currents, (pseudo-) scalar and/or tensor interactions
- usually added to $\mathcal{L}_{\mathrm{SM}}^{(t)}$

$\Rightarrow$ 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
  $\rightarrow$ narrow width approximation
  $\rightarrow$ 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 $B_s \to \phi(\to K^+K^-) + \bar{\ell}\ell$



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

1)	$q^2 = m^2_{\bar{\ell}\ell} = (p_{\bar{\ell}} + p_\ell)^2 = (p_B - p_{K^*})^2$	$4m^2_\ell \leqslant q^2 \leqslant (M_B - M_{K^*})^2$
2)	$\cos\theta_\ell$ with $\theta_\ell \angle(\vec{p}_B, \vec{p}_{\bar{\ell}})$ in $(\bar{\ell}\ell)$-c.m. system	$-1 \leqslant \cos\theta_\ell \leqslant 1$
3)	$\cos\theta_{K^*}$ with $\theta_{K^*} \angle(\vec{p}_B, \vec{p}_K)$ in $(K\pi)$-c.m. system	$-1 \leqslant \cos\theta_{K^*} \leqslant 1$
4)	$\phi\ \angle(\vec{p}_K \times \vec{p}_\pi, \vec{p}_{\bar{\ell}} \times \vec{p}_\ell)$ in B-RF	$-\pi \leqslant \phi \leqslant \pi$

Angular distribution

diff. angular distribution (except $\mathcal{O}_{T,T5}$)

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

$$+ I_3 \sin^2\theta_{K^*} \sin^2\theta_\ell \cos 2\phi + I_4 \sin 2\theta_{K^*} \sin 2\theta_\ell \cos\phi + I_5 \sin 2\theta_{K^*} \sin\theta_\ell \cos\phi$$

$$+ (I_6^s \sin^2\theta_{K^*} + I_6^c \cos^2\theta_{K^*})\cos\theta_\ell + I_7 \sin 2\theta_{K^*} \sin\theta_\ell \sin\phi$$

$$+ I_8 \sin 2\theta_{K^*} \sin 2\theta_\ell \sin\phi + I_9 \sin^2\theta_{K^*} \sin^2\theta_\ell \sin 2\phi$$

$\Rightarrow$ in principle $2 \times (12 + 12) = 48$ q^2-dependent observables $I_i^{(j)}(q^2)$
when including A) CP-conjugate decay and B) for each $\ell = e, \mu$

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

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

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

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

CP-odd $\Rightarrow$ CP-asymmetries $\sim d^4(\Gamma + \bar{\Gamma})$ from untagged B samples

Observables - I

Combining decay + CP-conjugated decay

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

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

- normalisation to CP-ave rate → reduce form factor dependence

  BUT better suited normalisations possible (examples later)

- if full angular fit from experimental data possible then

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

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

Observables - II

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

- $$\frac{d\langle\Gamma\rangle}{d\phi} = \frac{3}{8\pi}\left\{\langle I_1\rangle - \frac{\langle I_2\rangle}{3} + \frac{4}{3}\langle I_3\rangle\cos 2\phi + \frac{4}{3}\langle I_9\rangle \sin 2\phi\right\}$$

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

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

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

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

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

OBSERVABLES - III

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

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

- lepton forward-backward asymmetry

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

- lepton forward-backward CP-asymmetry

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

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

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

- "transversity observables"

$$A_T^{(2)} = \frac{S_3}{2S_2^s}$$

$$A_T^{(3)} = \left(\frac{4S_4^2 + S_7^2}{-2S_2^c\,(2S_2^s + S^3)}\right)^{1/2}$$

$$A_T^{(4)} = \left(\frac{S_5^2 + 4S_8^2}{4S_4^2 + S_7^2}\right)^{1/2}$$

- lepton-flavour e, μ-non-universal

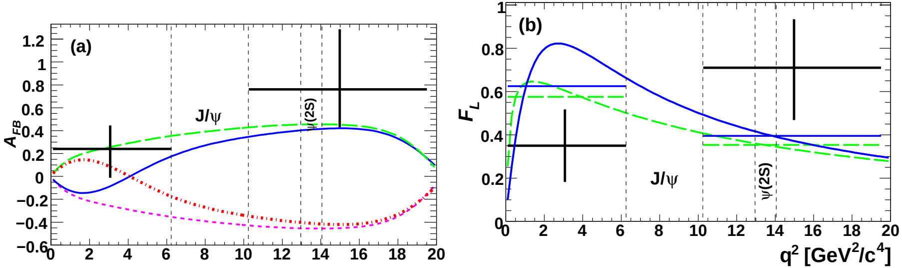
$$R_{K^*} = \frac{d\Gamma[B \to K^* \bar{e}e]}{dq^2} \Big/ \frac{d\Gamma[B \to K^* \bar{\mu}\mu]}{dq^2}$$

- isospin asymmetry

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

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

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

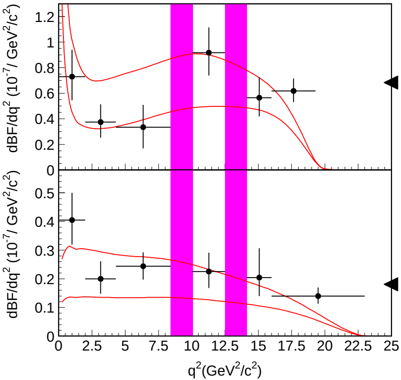


- 2 bins: low-$q^2 \in [0.1 - 6.25]$ GeV^2 and high-$q^2 > 10.24$ GeV^2
  $\Rightarrow (27 \pm 6) + (37 \pm 10) = 64$ events
- veto of J/ψ and ψ' regions: background $B \to K^*(\bar{c}c) \to K^*\bar{\ell}\ell$
- angular analysis in each q^2-bin in θ_ℓ and θ_{K^*} ⇒ fit F_L and $A_{\rm FB}$

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

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

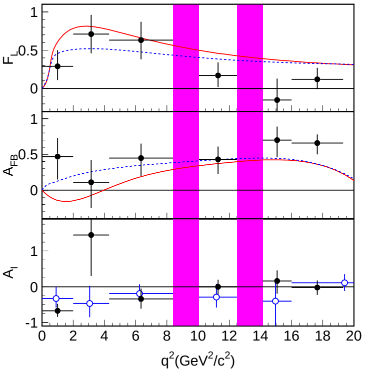
Analysis of 657 M $B\bar{B}$ pairs = 605 fb^{-1} $\rightarrow$ search all channels $B^{+,0}$, $K^{(*),+,-}$ and $\ell = e,\ \mu$



◀ $B \rightarrow K^* \bar{\ell}\ell$

red = SM

◀ $B \rightarrow K \bar{\ell}\ell$

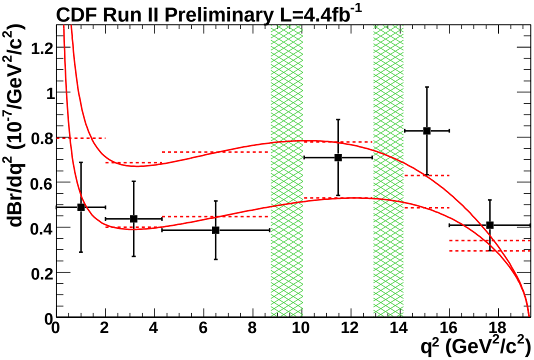


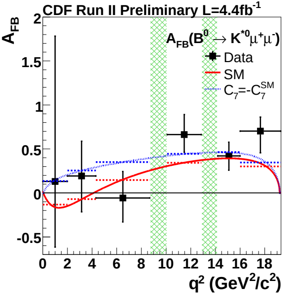
- 6 bins $\Rightarrow$ 247 events (121 @ $q^2 > 14$ GeV^2)
- angular analysis in each q^2-bin in θ_ℓ and θ_{K^*} $\Rightarrow$ fit F_L and $A_{\rm FB}$
- all-q^2 extrapolated results:

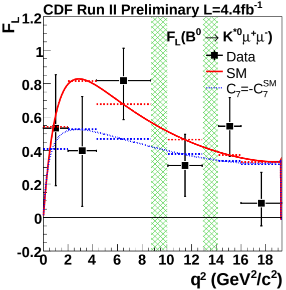
$$Br = (10.7^{+1.1}_{-1.0} \pm 0.09) \times 10^{-7}, \qquad A_{\rm CP} = -0.10 \pm 0.10 \pm 0.01,$$

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

- 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







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 $\text{fb}^{-1} \to (9-13)$ fb^{-1}
(more data, improved analysis and final states)

will there be a RUN III ???

LHCb prospects for 2.0 fb^{-1} = nominal year running

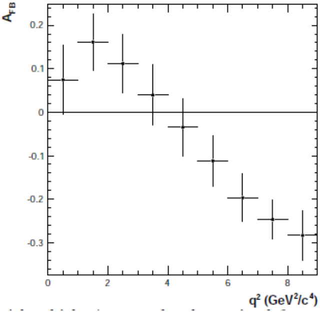
$\ell = \mu$ expected events after selection [arXiv:0912.4179]

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

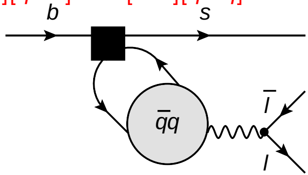
q_0^2 of $A_{\rm FB}$ expected with stat. unc. of ± 0.5 GeV^2
(B factory uncertainty expected with 0.3 fb^{-1})



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

perhaps also [ATLAS, CMS, Belle II, Super-B]

general theory problem in $b \to s + \bar{\ell}\ell$ due to Op's: $[\bar{s}\Gamma q][\bar{q}\Gamma' b]$ and $[\bar{s}\Gamma b][\bar{q}\Gamma' q]$



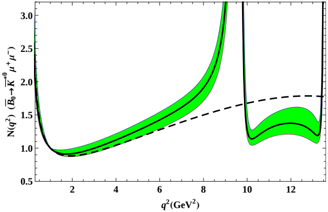
LONG DISTANCE - $(\bar{q}q)$-RESONANCE BACKGROUND

$$\mathcal{A}[B \to V + \bar{\ell}\ell] = \mathcal{A}[B \to V + \bar{\ell}\ell]_{SD-FCNC}$$
$$+ \mathcal{A}[B \to V + (\bar{q}q) \to V + \bar{\ell}\ell]_{LD}$$

for $B \to K^* + \bar{\ell}\ell$ $\quad (q^2_{max} \approx 19.2\ \text{GeV}^2)$:

$q = u, d, s$ light resonances below $q^2 \leqslant 1$ GeV^2
suppr. by small QCD-peng. Wilson coeff. or CKM $\hat{\lambda}_u$

$q = c$ start @ $q^2 \sim (M_{J/\psi})^2 \approx 9.6$ GeV^2, $(M_{\psi'})^2 \approx 13.6$ GeV^2



Khodjamirian/Mannel/Pivovarov/Wang arXiv:1006.4945

- OPE near light-cone incl. soft-gluon emission (non-local operator)
- up to (15-20) % in rate for $1 < q^2 < 6$ GeV^2

$\Rightarrow$ should be included in future analysis

q^2 - REGIONS

K^*-energy in B-rest frame: $E_{K^*} = (M_B^2 + M_{K^*}^2 - q^2)/(2M_B)$

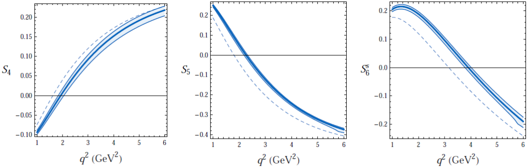
low-q^2	high-q^2
$q^2 \ll M_B^2$	$(M_B - M_{K^*})^2 - 2M_B\Lambda_{\rm QCD} \lesssim q^2$
$E_{K^*} \sim M_B/2$ large recoil	$E_{K^*} \sim M_{K^*} + \Lambda_{\rm QCD}$ low recoil
$q^2 \in [1, 6]$ GeV^2 ($E_{K^*} > 2.1$ GeV) QCDF, SCET	$q^2 \gtrsim 14.0$ GeV^2 OPE + HQET

low-q^2 above $q = u, d, s$ resonances and below $q = c$ resonances:
$\mathcal{A}[B \to V + (\bar{q}q) \to V + \bar{\ell}\ell]_{LD}$ treated within $(\Lambda_{\rm QCD}/m_c)^2$ expansion

high-q^2 quark-hadron duality + OPE

CP-averaged

(Altmannshofer et al. arXiv:0811.1214)



positions of zero crossings:

- $q_0^2[S_4] = 1.94^{+0.12}_{-0.10}$ GeV^2
- $q_0^2[S_5] = 2.24^{+0.06}_{-0.08}$ GeV^2
- $q_0^2[S_6^s] = 3.90^{+0.11}_{-0.12}$ GeV^2

CP-asymmetries – integ. $q^2 \in [1, 6]$ GeV^2

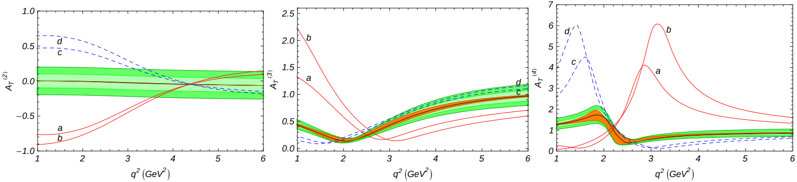
(CB/Hiller/Piranishvili arXiv:0805.2525)

	$\langle A_{\rm CP} \rangle$	$\langle A_4^D \rangle$	$\langle A_5^D \rangle$	$\langle A_6 \rangle$	$\langle A_7^D \rangle$	$\langle A_8^D \rangle$
$\times 10^{-3}$	$4.2^{+1.7}_{-2.5}$	$-1.8^{+0.3}_{-0.3}$	$7.6^{+1.5}_{-1.6}$	$-6.4^{+2.2}_{-2.7}$	$-5.1^{+2.4}_{-1.6}$	$3.5^{+1.4}_{-2.0}$

$A_i \sim \mathrm{Im}[\hat{\lambda}_u] \approx \bar{\eta}\lambda^2 \sim 10^{-2}$ very tiny → “quasi-null test” of SM

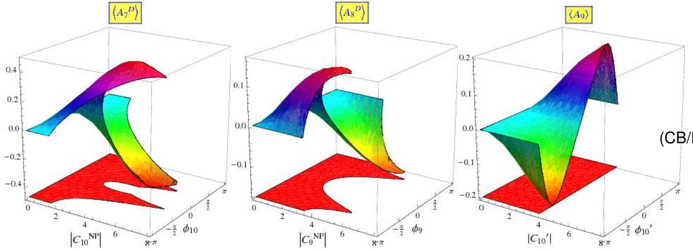
“transversity observables”

(Egede et al. arXiv:0807.2589 + 1005.0571)



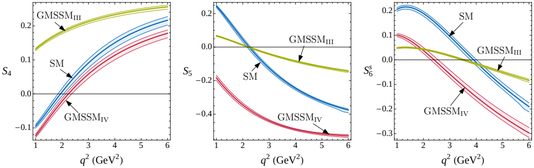
specially “designed”: A) FF-cancelation at LO in QCDF and B) sensitivity to BSM operators

LOW-q^2 – II – SOME BSM STUDIES



Model-independent

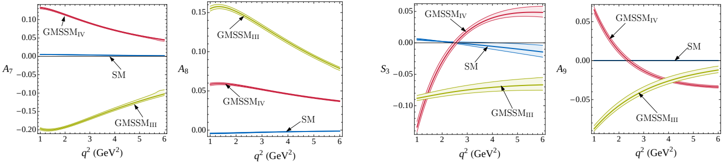
(CB/Hiller/Piranishvili arXiv:0805.2525)



General MSSM

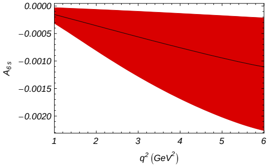
(Altmannshofer et al. arXiv:0811.1214)

flavour violation in $\tilde{d}$-mass
$(\delta_d)_{32}^{LR} \longrightarrow C_{7'}$ from $\tilde{d} - \tilde{g}$ contr.

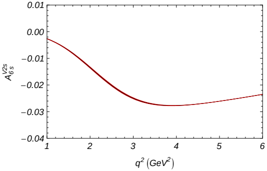


Alternative ratios → better cancelation of FF dependences (Egede et al. arXiv:0807.2589 + 1005.0571)

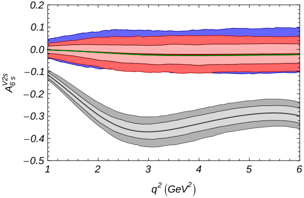
$$A_{6s} = \frac{I_6^{(s)} - \bar{I}_6^{(s)}}{d(\Gamma + \bar{\Gamma})/dq^2}$$



$$A_{6s}^{V2s} = \frac{I_6^{(s)} - \bar{I}_6^{(s)}}{I_2^{(s)} + \bar{I}_2^{(s)}}$$



SM (colour) vs BSM model-indep. $|C_{10}^{\rm NP}| = 1.5$ and $\phi_{10}^{\rm NP} = \frac{\pi}{2}$ (grey)

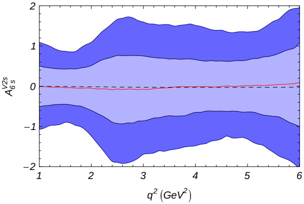


theory predictions includes pert., FF and $\Lambda_{\rm QCD}/m_b$ unc.

reconstruction from 10 fb^{-1} simulated LHCb data (SM)

→ large exp. uncertainty

CP-violating obs. rather difficult @ LHCb



experimental uncertainty

Prospects for CP-averaged observables very promising – also sensitive to BSM weak phases

HIGH-q^2 – SM OPERATOR BASIS

OBSERVABLES $\sim A_i A_j^* \sim U_k \sim \rho_{1,2}$

$$\rho_1 \equiv \left| \mathcal{C}_9^{eff} + \kappa \frac{2\hat{m}_b}{\hat{s}} \mathcal{C}_7^{eff} \right|^2 + |\mathcal{C}_{10}|^2 , \qquad \rho_2 \equiv \mathrm{Re}\left(\mathcal{C}_9^{eff} + \kappa \frac{2\hat{m}_b}{\hat{s}} \mathcal{C}_7^{eff} \right) \mathcal{C}_{10}^*$$

$$I_2^c \sim U_1 = 2\rho_1 f_0^2, \qquad 2I_2^s + I_3 \sim U_2 = 2\rho_1 f_\perp^2, \qquad 2I_2^s - I_3 \sim U_3 = 2\rho_1 f_\parallel^2,$$

$$I_4 \sim U_4 = 2\rho_1 f_0 f_\parallel, \qquad I_5 \sim U_5 = 4\rho_2 f_0 f_\perp, \qquad I_6^s \sim U_6 = 4\rho_2 f_\parallel f_\perp,$$

$$I_7 = I_8 = I_9 = 0.$$

A) ρ_1 and ρ_2 are largely μ-scale independent and B) $f_{\perp,\parallel,0}$ FF-dependent

$\Rightarrow$ 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

$$V(q^2) = \frac{r_1}{1 - q^2/m_R^2} + \frac{r_2}{1 - q^2/m_{\rm fit}^2},$$

$$A_1(q^2) = \frac{r_2}{1 - q^2/m_{\rm fit}^2}, \qquad A_2(q^2) = \frac{r_1}{1 - q^2/m_{\rm fit}^2} + \frac{r_2}{(1 - q^2/m_{\rm fit}^2)^2}$$

HIGH-q^2 – "LONG-DISTANCE FREE"

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

$$H_T^{(1)} = \frac{U_4}{\sqrt{U_1 \cdot U_3}} = 1, \qquad H_T^{(2)} = \frac{U_5}{\sqrt{U_1 \cdot U_2}} = 2\,\frac{\rho_2}{\rho_1}, \qquad H_T^{(3)} = \frac{U_6}{\sqrt{U_2 \cdot U_3}} = 2\,\frac{\rho_2}{\rho_1},$$

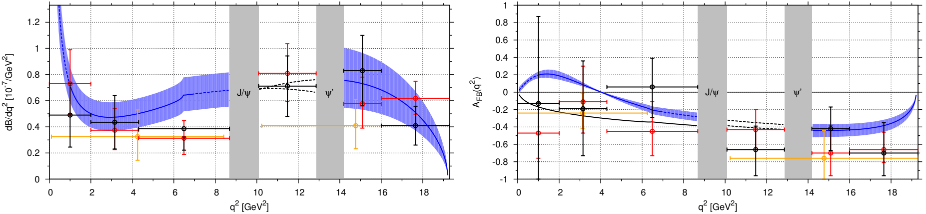
using extrapolated LCSR FF's assuming same uncertainties (Lattice results desireable)

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

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

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

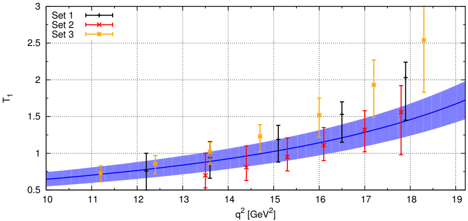
$$\langle H_T^{(3)} \rangle = -0.958 \pm 0.001\Big|_{\rm SL}\,{}^{+0.008}_{-0.006}\Big|_{\rm IWR}\,{}^{+0.003}_{-0.004}\Big|_{\rm SD}$$



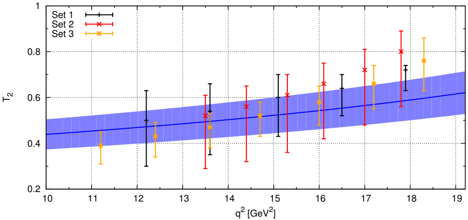
Data points from [Babar] [Belle] [CDF]

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

$$\frac{f_0}{f_\parallel} = \sqrt{\frac{U_1}{U_3}} = \frac{U_1}{U_4} = \frac{U_4}{U_3} = \frac{U_5}{U_6}, \qquad \frac{f_0}{f_\perp} = \sqrt{\frac{U_1}{U_2}}, \qquad \frac{f_\perp}{f_\parallel} = \sqrt{\frac{U_2}{U_3}} = \frac{\sqrt{U_1 U_2}}{U_4}$$

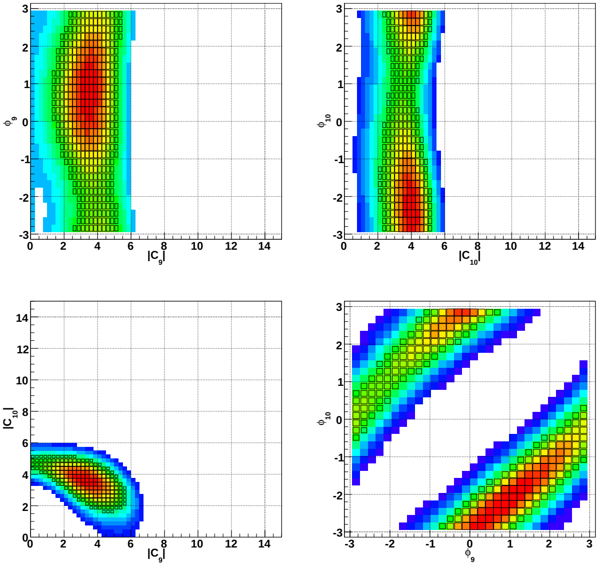


LCSR extrapolation (Ball/Zwicky hep-ph/0412079) of $T_1(q^2)$ and $T_2(q^2)$ to high-q^2 versus quenched Lattice (3 data sets from Becirevic/Lubicz/Mescia hep-ph/0611295)



new unquenced Lattice results to come → Liu/Meinel/Hart/Horgan/Müller/Wingate arXiv:0911.2370

Fit of C_9 and C_{10} - Present



Using $B \to K^* \bar{\ell}\ell$ data from Belle and CDF

- 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

Calculating on grid

$$-2 \ln \mathcal{L} = \sum_i \chi_i^2$$

95 % (68 % box) CL regions

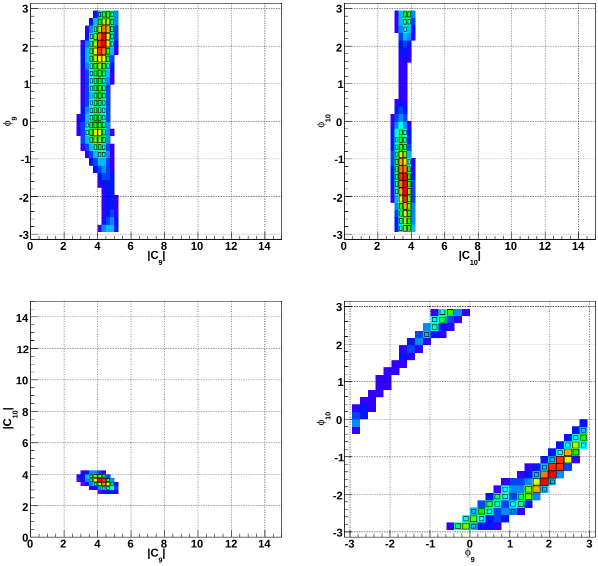
for

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

prelim. CB/Hiller/van Dyk

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

Fit of C_9 and C_{10} - Close Future?



Using $B \to K^* \bar{\ell}\ell$ data from Belle and CDF

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  $[1, 6]$ GeV^2
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- $|C_{9,10}| \in [0, 15]$
- $\phi_{7,9,10} \in [-\pi, +\pi]$

prelim. CB/Hiller/van Dyk

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

Conclusion

- 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 $B_s \to \phi(\to K^+K^-) + \bar{\ell}\ell$
- experimental situation expected to improve tremendously with LHCb, updates of BaBar, Belle and CDF to come
- 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:
  - are $(\bar{c}c)$-resonances 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

EOS = new Flavour tool @ TU Dortmund by Danny van Dyk et al.
http://project.het.physik.tu-dortmund.de/eos/
first stable release expected 2011

Backup slides

TRANSVERSITY AMPLITUDES (TA) - I

DECAY AMPLITUDE MIGHT BE DESCRIBED USING ...

...$B \to K^* + V^*(\to \bar{\ell}\ell)$

- K^* on-shell: 3 polarisations $\epsilon_{K^*}(m = +, -, 0)$
- V^* off-shell: 4 polarisations $\epsilon_{V^*}(n = +, -, 0, t)$ (t=time-like)

$$\mathcal{M}^{L,R}[B \to K^* + V^*(\to \bar{\ell}\ell)] \sim \sum_{m,n,n'} \epsilon^{*\mu}_{K^*}(m)\, \epsilon^{*\nu}_{V^*}(n)\, \mathcal{M}_{\mu\nu}\, \epsilon^{\alpha}_{V^*}(n')\, g_{nn'}\, [\bar{\ell}\, \gamma_\alpha P_{L,R}\, \ell]$$

Transversity amplitudes

$$A^{L,R}_{\perp,\parallel} = [\mathcal{M}^{L,R}_{(+,+)} \mp \mathcal{M}^{L,R}_{(-,-)}]/\sqrt{2}, \qquad A^{L,R}_0 = \mathcal{M}^{L,R}_{(0,0)}, \qquad A_t = \mathcal{M}_{(0,t)}$$

- $\mathcal{M}_{(m,n)} \equiv \epsilon^{*\mu}_{K^*}(m)\, \epsilon^{*\nu}_{V^*}(n)\, \mathcal{M}_{\mu\nu}$
- includes all EFT operators $\sim [\bar{\ell}\, \{\gamma_\mu,\ \gamma_\mu\gamma_5,\ \gamma_5\}\, \ell]$

... for scalar exchange $B \to K^* + S(\to \bar{\ell}\ell) \sim [\bar{\ell}\, 1\, \ell]$ additional TA: A_S

$\Rightarrow$ all observables are functions $I_i^{(j)}(q^2) = f_{ij}(A_a A_b^*)[q^2]$

of 8 TA's $A^{L,R}_\perp$, $A^{L,R}_\parallel$, $A^{L,R}_0$, A_t, A_S

Transversity amplitudes (TA) - II

Dependence of TA from Wilson coefficients (neglecting T, $T5$-operators)

- $A_{\perp,\|,0} = A_{\perp,\|,0}(C_{7,7',9,9',10,10'})$
- $A_t = A_t(C_{10,10',P,P'})$ $\Rightarrow$ only $C_{7,9,10}$ contribute in SM!!!
- $A_S = A_S(C_{S,S'})$

Limit $m_\ell \to 0$

- $I_1^s = 3I_2^s$, $I_1^c = -I_2^c$ and $I_6^c = 0$
- $A_t \to A_t(C_{P,P'})$

T-odd observables $\sim \cos\delta_s \sin\delta_W$ (strong phase δ_s)

$$A_7 \sim \left[\mathrm{Im}(A_0^L A_\|^{L*}) - (L \to R) + \frac{m_\ell}{\sqrt{q^2}}\mathrm{Im}(A_\perp^L A_S^* + A_\perp^R A_S^*)\right] - (\delta_W \to -\delta_W)$$

$$A_8 \sim \left[\mathrm{Im}(A_0^L A_\perp^{L*}) + (L \to R)\right] - (\delta_W \to -\delta_W)$$

$$A_9 \sim \left[\mathrm{Im}(A_\perp^L A_\|^{L*}) + (L \to R)\right] - (\delta_W \to -\delta_W)$$

$\Rightarrow$ sensitive to BSM weak phases for small strong phases!!! CB/Hiller/Piranishvili arXiv:0805.2525

LOW-q^2 – QCDF

QCD Factorisation (QCDF) = (large recoil + heavy quark) limit

FF RELATIONS

7 QCD $B \to K^*$ FFs $V, A_{0,1,2}, T_{1,2,3} \to$ 2 universal $\xi_{\perp,\parallel}$ FFs

$$F_i(q^2) \sim T_i^I \times \xi(q^2) + \phi_B \otimes T_i^{II} \otimes \phi_{K^*} + \mathcal{O}(\Lambda_{\text{QCD}}/m_b)$$

T_i^I, T_i^{II} perturbatively in α_s, ϕ_{B,K^*} meson distribution amplitudes

Beneke/Feldmann hep-ph/0008255

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

$$\langle \bar{\ell}\ell \bar{K}_a^* | H_{\text{eff}}^{(i)} | \bar{B} \rangle \sim C_a^{(i)} \times \xi_a + \phi_B \otimes T_a^{(i)} \otimes \phi_{a,K^*} + \mathcal{O}(\Lambda_{\text{QCD}}/m_b)$$

$C_a^{(i)}$, $T_a^{(i)}$ perturbatively in α_s ($a = \perp, \parallel$, $i = u, t$)

@ NNLO QCD in Beneke/Feldmann/Seidel hep-ph/0106067, hep-ph/0412400

HIGH-q^2 OPE + HQET – I

FRAMEWORK DEVELOPED IN GRINSTEIN/PIRJOL HEP-PH/0404250

1) OPE in $\Lambda_{\rm QCD}/Q$ with $Q = \{m_b, \sqrt{q^2}\}$ + matching on HQET for 4-quark Op's

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

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

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

(in analogy to heavy quark expansion)

$\mathcal{Q}_{j,\alpha}^{(k)}$	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	$\alpha_s^0(Q)$

inlcuded,
unc. estimate by naive pwr cont.

2) HQET FF-relations at sub-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 OPE + HQET – II

⇒ only SM operator basis and $m_\ell = 0$:

⇒ convenient to use U_k which are simple lin. comb. of $I_i^{(j)}$)

$$U_1 = |A_0^L|^2 + |A_0^R|^2, \qquad U_4 = \mathrm{Re}(A_0^L A_\parallel^{L*} + A_0^{R*} A_\parallel^R), \qquad U_7 = \mathrm{Im}(A_0^L A_\parallel^{L*} + A_0^{R*} A_\parallel^R),$$

$$U_2 = |A_\perp^L|^2 + |A_\perp^R|^2, \qquad U_5 = \mathrm{Re}(A_0^L A_\perp^{L*} - A_0^{R*} A_\perp^R), \qquad U_8 = \mathrm{Im}(A_0^L A_\perp^{L*} - A_0^{R*} A_\perp^R),$$

$$U_3 = |A_\parallel^L|^2 + |A_\parallel^R|^2, \qquad U_6 = \mathrm{Re}(A_\parallel^L A_\perp^{L*} - A_\parallel^{R*} A_\perp^R), \qquad U_9 = \mathrm{Im}(A_\parallel^L A_\perp^{L*} - A_\parallel^{R*} A_\perp^R),$$

TRANSVERSITY AMPLITUDES - SM OP'S ONLY

$$A_\perp^{L,R} = +iNM_B\, c_{L,R}\, f_\perp, \qquad A_\parallel^{L,R} = -iNM_B\, c_{L,R}\, f_\parallel, \qquad A_0^{L,R} = -iNM_B\, c_{L,R}\, f_0$$

2 universal "short-distance" coeff's (sub-lead. $\Lambda_{\rm QCD}/m_b$ corr. only in term $\sim C_7^{eff}$)

$$c_{L,R} = (\mathcal{C}_9^{eff} \mp \mathcal{C}_{10}) + \kappa \frac{2\hat{m}_b}{\hat{s}}\, \mathcal{C}_7^{eff}$$

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

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

LITERATURE - INCOMPLETE

- $b \to q + \bar{\ell}\ell$ in QCDF @ low-q^2: Beneke/Feldmann/Seidel hep-ph/0106067, hep-ph/0412400
- $b \to s + \bar{\ell}\ell$ in SCET @ low-q^2: Ali/Kramer/Zhu hep-ph/0601034
- $b \to s + \bar{\ell}\ell$ in OPE + HQET @ high-q^2: Grinstein/Pirjol hep-ph/0404250
- $b \to s + \bar{\ell}\ell$ and $\bar{c}c$-resonances:
  Buchalla/Isidori/Rey hep-ph/9705253
  Beneke/Buchalla/Neubert/Sachrajda arXiv:0902.4446
  Khodjamirian/Mannel/Pivovarov/Wang arXiv:1006.4945
- $B \to V_{on-shell}(\to P_1 P_2) + \bar{\ell}\ell$
  Krüger/Sehgal/Sinha/Sinha hep-ph/9907386 : CP asymmetries @ all-q^2
  Feldmann/Matias hep-ph/0212158 : isospin asymmetry A_I @ low-q^2
  Krüger/Matias hep-ph/0502060 : transv. observables @ low-q^2
  Kim/Yoshikawa arXiv:0711.3880 : @ all-q^2, also $B \to S_{on-shell}(\to P_1 P_2) + \bar{\ell}\ell$
  Bobeth/Hiller/Piranishvili arXiv:0805.2525 : CP asymmetries @ low-q^2
  Egede/Hurth/Matias/Ramon/Reece arXiv:0807.2589 : LHCb and transv. observables @ low-q^2
  Altmannshofer/Ball/Bharucha/Buras/Straub/Wick arXiv:0811.1214 : CP-ave + asy @ low-q^2 + (pseudo-) scalar Op's
  Alok/Dighe/Ghosh/London/Matias/Nagashima/Szynkman arXiv:0912.1382
  Bharucha/Reece arXiv:1002.4310 : early LHCb potential @ low-q^2
  Egede/Hurth/Matias/Ramon/Reece arXiv:1005.0571 : LHCb and transv. observables@ low-q^2
  Bobeth/Hiller/van Dyk arXiv:1006.5013 : @ high-q^2
  Alok et al. arXiv:1008.2367 : @ all-q^2 + tensor Op's