Rare $b \to s\,\ell^+\ell^-$ decays

– getting ready –

Christoph Bobeth

TU Munich – Universe Cluster

Seminar
Edinburgh
University

Outline

I) Introduction: EFT of $|\Delta B| = |\Delta S| = 1$ decays

II) Experimental status & measurements

$$B \to K^*(\to K\pi)\,\ell^+\ell^-, \quad B \to K\,\ell^+\ell^-, \quad B_s \to \mu^+\mu^-$$

III) Exclusive decays $B \to K^{(*)}\ell^+\ell^-$

A) Low- & high-q^2 regions

B) Form factor relations

C) Optimized observables in $B \to K^*(\to K\pi)\,\ell^+\ell^-$

IV) Fits and implications

Effective Theory of $|\Delta B| = |\Delta S| = 1$ decays

Flavour changes in SM – only via $W^\pm$ exchange

$U_i = \{u, c, t\}$:

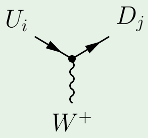
$Q_U = +2/3$

$D_j = \{d, s, b\}$:

$Q_D = -1/3$

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

$\sim$ Cabibbo-Kobayashi-Maskawa (CKM) matrix



Flavour changes in SM – only via $W^\pm$ exchange

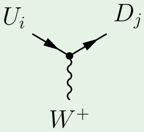
$U_i = \{u, c, t\}$:

$Q_U = +2/3$

$D_j = \{d, s, b\}$:

$Q_D = -1/3$

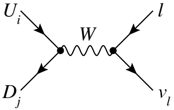
$$\mathcal{L}_{\rm CC} = \frac{g_2}{\sqrt{2}} (\bar{u}, \bar{c}, \bar{t}) \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \gamma^\mu P_L \begin{pmatrix} d \\ s \\ b \end{pmatrix} W_\mu^+$$

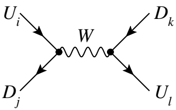


$\sim$ Cabibbo-Kobayashi-Maskawa (CKM) matrix

Tree: only $U_i \to D_j$ & $D_i \to U_j$

$Q_i \neq Q_j \quad \Rightarrow \quad$ charged current (CC)





$H \to \ell \nu_\ell$

$H_1 \to H_2 + \ell \nu_\ell$

$H_1 \to H_2 H_3$

Flavour changes in SM – only via $W^{\pm}$ exchange

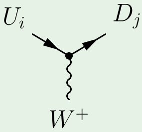
$U_i = \{u, c, t\}$:

$Q_U = +2/3$

$D_j = \{d, s, b\}$:

$Q_D = -1/3$

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



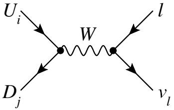
$\sim$ Cabibbo-Kobayashi-Maskawa (CKM) matrix

Tree: only $U_i \to D_j$ & $D_i \to U_j$

$Q_i \neq Q_j \quad \Rightarrow \quad$ charged current (CC)

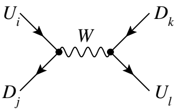
Loop: $D_i \to D_j$ (& $U_i \to U_j$)

$Q_i = Q_j \quad \Rightarrow \quad$ neutral current (FCNC)

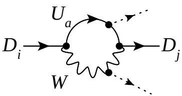


$H \to \ell \nu_\ell$

$H_1 \to H_2 + \ell \nu_\ell$

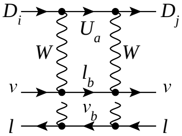


$H_1 \to H_2 H_3$



$H_1 \to H_2 + \{\gamma, Z, g\}$

$\{\gamma, Z, g\} \to \{\gamma, \bar{\ell}\ell, H_3\}$



$H_1 \to \bar{\ell}\ell$

$H_1 \to H_2 + \{\bar{\ell}\ell, \bar{\nu}\nu\}$

Flavour changes in SM – only via $W^\pm$ exchange

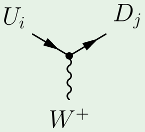
$U_i = \{u, c, t\}$:

$Q_U = +2/3$

$D_j = \{d, s, b\}$:

$Q_D = -1/3$

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



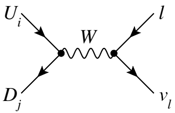
$\sim$ Cabibbo-Kobayashi-Maskawa (CKM) matrix

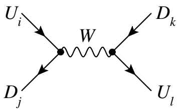
Tree: only $U_i \to D_j$ & $D_i \to U_j$

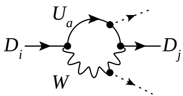
$Q_i \neq Q_j \quad \Rightarrow \quad$ charged current (CC)

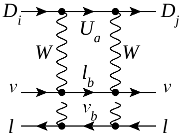
Loop: $D_i \to D_j$ (& $U_i \to U_j$)

$Q_i = Q_j \quad \Rightarrow \quad$ neutral current (FCNC)









$H \to \ell\nu_\ell$

$H_1 \to H_2 + \ell\nu_\ell$

$\mathcal{A} \sim G_F V_{ij}$

$H_1 \to H_2 H_3$

$\sim G_F V_{ij} V^*_{lk}$

$H_1 \to H_2 + \{\gamma, Z, g\}$

$\{\gamma, Z, g\} \to \{\gamma, \bar{\ell}\ell, H_3\}$

$\sim G_F g \sum_a V_{ai} V^*_{aj} f(m_a)$

$H_1 \to \bar{\ell}\ell$

$H_1 \to H_2 + \{\bar{\ell}\ell, \bar{\nu}\nu\}$

$\sim G_F g^2 \sum_{a,b} V_{ai} V^*_{aj} f(m_{a,b})$

Flavour changes in SM – only via $W^\pm$ exchange

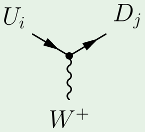
$U_i = \{u, c, t\}$:

$Q_U = +2/3$

$D_j = \{d, s, b\}$:

$Q_D = -1/3$

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



$\sim$ Cabibbo-Kobayashi-Maskawa (CKM) matrix

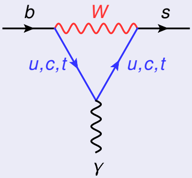
In the SM: FCNC-decays w.r.t. tree-decays are . . .

quantum fluctuations = loop-suppressed

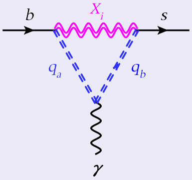
- $\Rightarrow$ no suppression of contributions beyond SM (BSM) wrt SM itself
- $\Rightarrow$ indirect search for BSM signals

BUT requires high precision, experimentally and theoretically !!!

SM



BSM



B-Hadron decays are a Multi-scale problem ...

... with hierarchical interaction scales

electroweak IA	$\gg$	ext. mom'a in B restframe	$\gg$	QCD-bound state effects
$M_W \approx 80$ GeV $M_Z \approx 91$ GeV		$M_B \approx 5$ GeV		$\Lambda_{\text{QCD}} \approx 0.5$ GeV

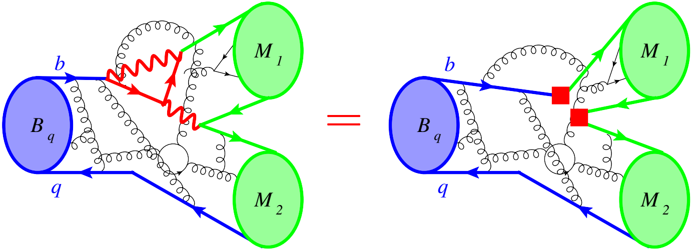
B-Hadron decays are a Multi-scale problem ...

... with hierarchical interaction scales

electroweak IA	$\gg$	ext. mom'a in B restframe
$M_W \approx 80$ GeV $M_Z \approx 91$ GeV		$M_B \approx 5$ GeV

electroweak scale is "short-distance = local" compared to external momenta

$\Rightarrow$ Effective theory of $|\Delta B| = |\Delta S| = 1$ decays $\Rightarrow$ separation of scales



$$+ \mathcal{O}\left(\frac{M_B^2}{M_W^2}\right)$$

renormalization group (RG) resums large QCD log's due to gluons

with virtuality $> M_B$ to all orders in α_s

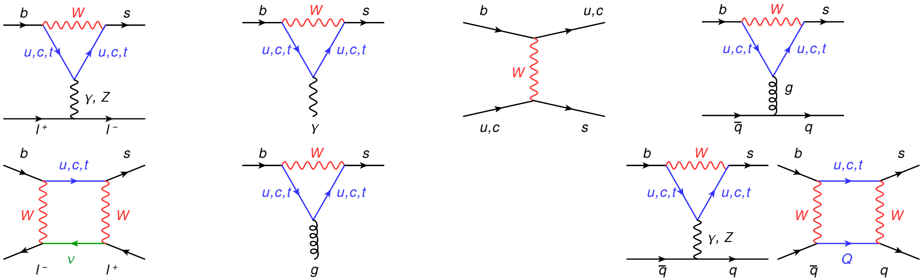
B-Hadron decays are a Multi-scale problem . . .

. . . with hierarchical interaction scales

electroweak IA	$\gg$	ext. mom'a in B restframe
$M_W \approx 80$ GeV $M_Z \approx 91$ GeV		$M_B \approx 5$ GeV

$$\mathcal{L}_{\rm eff} \sim G_F\, V_{\rm CKM} \times \left[\sum_{9,10} C_i^{\ell\bar\ell}\, \mathcal{O}_i^{\ell\bar\ell} + \sum_{7\gamma,\, 8g} C_i\, \mathcal{O}_i + \text{CC} + (\text{QCD \& QED-peng}) \right]$$

semi-leptonic | electro- & chromo-mgn | charged current | QCD & QED -penguin



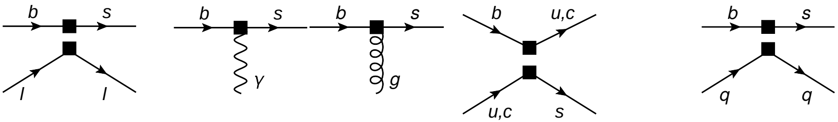
B-Hadron decays are a Multi-scale problem . . .

. . . with hierarchical interaction scales

electroweak IA	$\gg$	ext. mom'a in B restframe
$M_W \approx 80$ GeV $M_Z \approx 91$ GeV		$M_B \approx 5$ GeV

$$\mathcal{L}_{\text{eff}} \sim G_F\, V_{\text{CKM}} \times \left[\sum_{9,10} C_i^{\ell\bar{\ell}}\, \mathcal{O}_i^{\ell\bar{\ell}} + \sum_{7\gamma,\,8g} C_i\, \mathcal{O}_i + \text{CC} + (\text{QCD \& QED-peng})\right]$$

semi-leptonic | electro- & chromo-mgn | charged current | QCD & QED -penguin



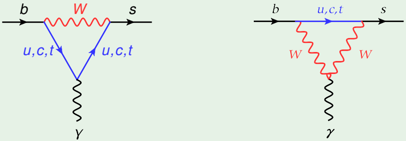
C_i = Wilson coefficients: contains short-dist. pmr's (heavy masses $M_t, \ldots$ – CKM factored out) and leading logarithmic QCD-corrections to all orders in α_s

$\Rightarrow$ in SM known up to next-to-next-to-leading order

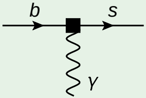
$\mathcal{O}_i$ = higher-dim. operators: flavour-changing coupling of light quarks

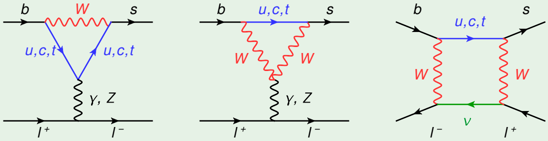
EFT (Effective Field Theory) in the SM (Standard Model) for . . .

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

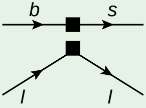


$\to C_{7\gamma} \times$





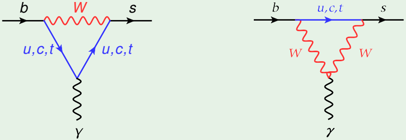
$\to C_{9,10}^{\ell\bar{\ell}} \times$



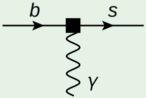
$$\mathcal{O}_{7\gamma} = \frac{e}{(4\pi)^2} m_b [\bar{s}\,\sigma^{\mu\nu} P_R\, b] F_{\mu\nu}, \qquad \mathcal{O}_{9,10}^{\ell\bar{\ell}} = \frac{\alpha_e}{4\pi} [\bar{s}\,\gamma^\mu P_L\, b][\bar{\ell}\,\gamma_\mu (1,\ \gamma_5)\,\ell]$$

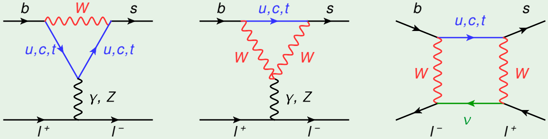
EFT (Effective Field Theory) in the SM (Standard Model) for ...

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

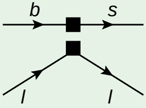


$\rightarrow C_{7\gamma} \times$





$\rightarrow C_{9,10}^{\ell\bar{\ell}} \times$



$$\mathcal{O}_{7\gamma} = \frac{e}{(4\pi)^2} m_b [\bar{s}\,\sigma^{\mu\nu} P_R\, b] F_{\mu\nu}, \qquad \mathcal{O}_{9,10}^{\ell\bar{\ell}} = \frac{\alpha_e}{4\pi} [\bar{s}\,\gamma^\mu P_L\, b][\bar{\ell}\,\gamma_\mu (1,\ \gamma_5)\,\ell]$$

and

- current-current op's $b \to s + Q\bar{Q}$, $(Q = u, c)$
- QCD penguin op's $b \to s + q\bar{q}$, $(q = u, d, s, c, b)$
- chromo-magnetic dipole $b \to s + gluon$

$\Rightarrow$ induce backgrounds

$b \to s + (q\bar{q}) \to s + \ell^+\ell^-$

vetoed in exp's for $q = c$: J/ψ and ψ'

More $b \to s + (\gamma, \ell^+\ell^-)$ operators beyond the SM . . .

. . . frequently considered in model-(in)dependent searches

SM' = χ-flipped SM analogues

$$\mathcal{O}_{7'\gamma} = \frac{e}{(4\pi)^2} m_b [\bar{s}\,\sigma_{\mu\nu} P_L\, b] F^{\mu\nu}, \qquad \mathcal{O}^{\ell\bar\ell}_{9',10'} = \frac{\alpha_e}{4\pi} [\bar{s}\,\gamma^\mu P_R\, b][\bar\ell\,(\gamma^\mu, \gamma^\mu\gamma_5)\,\ell]$$

S + P = scalar + pseudoscalar

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

T + T5 = tensor

$$\mathcal{O}^{\ell\bar\ell}_{T} = \frac{\alpha_e}{4\pi} [\bar{s}\,\sigma_{\mu\nu}\, b][\bar\ell\,\sigma^{\mu\nu}\,\ell], \qquad \mathcal{O}^{\ell\bar\ell}_{T5} = \frac{\alpha_e}{4\pi}\, i\, \frac{\varepsilon^{\mu\nu\alpha\beta}}{2} [\bar{s}\,\sigma_{\mu\nu}\, b][\bar\ell\,\sigma_{\alpha\beta}\,\ell]$$

new Dirac-structures beyond SM:

- SM' : right-handed currents
- S + P : higgs-exchange & box-type diagrams
- T + T5 : box-type diagrams, Fierzed scalar tree exchange

More $b \to s + (\gamma, \ell^+\ell^-)$ operators beyond the SM ...

... frequently considered in model-(in)dependent searches

SM' = χ-flipped SM analogues

$$\mathcal{O}_{7'\gamma} = \frac{e}{(4\pi)^2} m_b [\bar{s}\,\sigma_{\mu\nu} P_L\, b] F^{\mu\nu}, \qquad \mathcal{O}^{\ell\bar\ell}_{9',10'} = \frac{\alpha_e}{4\pi} [\bar{s}\,\gamma^\mu P_R\, b][\bar\ell\,(\gamma^\mu, \gamma^\mu\gamma_5)\,\ell]$$

S + P = scalar + pseudoscalar

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

T + T5 = tensor

$$\mathcal{O}^{\ell\bar\ell}_{T} = \frac{\alpha_e}{4\pi} [\bar{s}\,\sigma_{\mu\nu}\, b][\bar\ell\,\sigma^{\mu\nu}\,\ell], \qquad \mathcal{O}^{\ell\bar\ell}_{T5} = \frac{\alpha_e}{4\pi}\, i\, \frac{\varepsilon^{\mu\nu\alpha\beta}}{2} [\bar{s}\,\sigma_{\mu\nu}\, b][\bar\ell\,\sigma_{\alpha\beta}\,\ell]$$

new Dirac-structures beyond SM:

- SM' : right-handed currents
- S + P : higgs-exchange & box-type diagrams
- T + T5 : box-type diagrams, Fierzed scalar tree exchange

More $b \to s + (\gamma,\, \ell^+\ell^-)$ operators beyond the SM ...

... frequently considered in model-(in)dependent searches

SM' = χ-flipped SM analogues

$$\mathcal{O}_{7'\gamma} = \frac{e}{(4\pi)^2} m_b [\bar{s}\,\sigma_{\mu\nu} P_L\, b] F^{\mu\nu}, \qquad \mathcal{O}^{\ell\bar{\ell}}_{9',10'} = \frac{\alpha_e}{4\pi} [\bar{s}\,\gamma^\mu P_R\, b][\bar{\ell}\,(\gamma^\mu, \gamma^\mu\gamma_5)\,\ell]$$

S + P = scalar + pseudoscalar

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

T + T5 = tensor

$$\mathcal{O}^{\ell\bar{\ell}}_{T} = \frac{\alpha_e}{4\pi} [\bar{s}\,\sigma_{\mu\nu}\, b][\bar{\ell}\,\sigma^{\mu\nu}\,\ell], \qquad \mathcal{O}^{\ell\bar{\ell}}_{T5} = \frac{\alpha_e}{4\pi}\, i\, \frac{\varepsilon^{\mu\nu\alpha\beta}}{2} [\bar{s}\,\sigma_{\mu\nu}\, b][\bar{\ell}\,\sigma_{\alpha\beta}\,\ell]$$

new Dirac-structures beyond SM:

- SM' : right-handed currents
- S + P : higgs-exchange & box-type diagrams
- T + T5 : box-type diagrams, Fierzed scalar tree exchange

Extension of EFT beyond the SM ...

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

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

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

Extension of EFT beyond the SM . . .

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

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

⇒ ΔC_i . . . NP contributions to SM C_i

⇒ $\sum_{\rm NP} C_j \mathcal{O}_j$ . . . NP operators (e.g. $C'_{7,9,10}$, $C^{(\prime)}_{S,P}$, . . .)

⇒ ??? . . . additional light degrees of freedom (⇐ not pursued in the following)

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)

C_i are correlated, depend on fundamental parameters

model-indep. extending SM EFT-Lagrangian → new C_j

C_j are UN-correlated free parameters

Extension of EFT beyond the SM . . .

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

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

$\Rightarrow$ ΔC_i . . . NP contributions to SM C_i

$\Rightarrow$ $\sum_{\rm NP} C_j \mathcal{O}_j$ . . . NP operators (e.g. $C'_{7,9,10}$, $C^{(\prime)}_{S,P}$, . . .)

$\Rightarrow$??? . . . additional light degrees of freedom ($\Leftarrow$ not pursued in the following)

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)

C_i are correlated, depend on fundamental parameters

model-indep. extending SM EFT-Lagrangian $\to$ new C_j

C_j are UN-correlated free parameters

Experimental results

$B \to K^* \ell^+ \ell^-$

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

$B_s \to \mu^+ \mu^-$

$\Delta B = 1$ FCNC's: Rich phenomenology ...

$b \to s + \gamma$

$B \to K^*\gamma \quad (B_s \to \phi\gamma)$

– Br
– time-dep. CP asy's: S, C, H
– iso-spin asymmetry Δ_{0-}

$B \to X_s\gamma$

– Br, $\mathrm{d}Br/\mathrm{d}E_\gamma$
– A_{CP} in $B \to X_s\gamma$ and $B \to X_{s+d}\gamma$

$B_s \to \gamma\gamma$

– Br (A_{CP})

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

$B_s \to \ell^+\ell^-$: Br

$B \to K\,\ell^+\ell^-$: $\mathrm{d}Br/\mathrm{d}q^2$, $A_{\mathrm{FB}}(q^2)$, $F_H(q^2)$

$B \to K^*(\to K\pi)\,\ell^+\ell^- \quad (B_s \to \phi(\to K\bar{K})\,\ell^+\ell^-)$

– $\mathrm{d}Br/\mathrm{d}q^2$, $A_{\mathrm{FB}}(q^2)$, $F_{L,T}(q^2)$, ...
– $\mathrm{d}^4 Br/\mathrm{d}q^2\,\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\phi \to$ 12 angular obsv's $J_{1,\ldots,9}^{(s,c)}$

$\to$ optimized obsv's $A_T^{(2,3,4,\mathrm{re},\mathrm{im})}$, $P_{1,\ldots,6}$, $H_T^{(1,\ldots,5)}$

$B \to X_s\,\ell^+\ell^-$: $\mathrm{d}Br/\mathrm{d}q^2$, $A_{\mathrm{FB}}(q^2)$, $H_{T,L}(q^2)$

$\Delta B = 1$ FCNC's: Rich phenomenology ...

$b \to s + \gamma$

$B \to K^* \gamma \qquad (B_s \to \phi\gamma)$

– Br

– time-dep. CP asy's: S, C, H

– iso-spin asymmetry Δ_{0-}

$B \to X_s \gamma$

– Br, $\mathrm{d}Br/\mathrm{d}E_\gamma$

– $A_{\rm CP}$ in $B \to X_s\gamma$ and $B \to X_{s+d}\gamma$

$B_s \to \gamma\gamma$

– Br ($A_{\rm CP}$)

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

$B_s \to \ell^+\ell^-$: Br

$B \to K\,\ell^+\ell^-$: $\mathrm{d}Br/\mathrm{d}q^2,\quad A_{\rm FB}(q^2),\quad F_H(q^2)$

$B \to K^*(\to K\pi)\,\ell^+\ell^- \qquad (B_s \to \phi(\to K\bar{K})\,\ell^+\ell^-)$

– $\mathrm{d}Br/\mathrm{d}q^2,\quad A_{\rm FB}(q^2),\quad F_{L,T}(q^2),\ \ldots$

– $\mathrm{d}^4 Br/\mathrm{d}q^2\,\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\phi \to$ 12 angular obsv's $J^{(s,c)}_{1,\ldots,9}$

$\to$ optimized obsv's $A_T^{(2,3,4,\mathrm{re},\mathrm{im})},\quad P_{1,\ldots,6},\quad H_T^{(1,\ldots,5)}$

$B \to X_s\,\ell^+\ell^-$: $\mathrm{d}Br/\mathrm{d}q^2,\quad A_{\rm FB}(q^2),\quad H_{T,L}(q^2)$

... to test short-distance flavor couplings C_i:

$i = 7, 7'$

$i = 7^{(\prime)}, 9^{(\prime)}, 10^{(\prime)}, S^{(\prime)}, P^{(\prime)}, T(5), \ldots$

BUT need non-perturbative hadronic input:

Form factors: $(B \to K) \to f_{+,T,0}$ and $(B \to K^*,\ B_s \to \phi) \to V,\ A_{0,1,2},\ T_{1,2,3}$

Decay constants and LCDA's : $B_{d,s},\ K,\ K^*,\ \phi,\ \ldots$

Heavy quark expansion parameters : $\lambda_{1,2}$, ..., Shape-functions ...

Experimental data: $b \to s\,\ell^+\ell^-$ – number of events

# of evts	BaBar 2012 471 M $\bar{B}B$	Belle 2009 605 fb^{-1}	CDF 2011 9.6 fb^{-1}	LHCb 2011/12 1 fb^{-1}
$B^0 \to K^{*0}\,\ell\bar{\ell}$	$137 \pm 44^\dagger$	$247 \pm 54^\dagger$	288 ± 20	900 ± 34
$B^+ \to K^{*+}\,\ell\bar{\ell}$			24 ± 6	76 ± 16
$B^+ \to K^+\,\ell\bar{\ell}$	$153 \pm 41^\dagger$	$162 \pm 38^\dagger$	319 ± 23	1232 ± 40
$B^0 \to K_S^0\,\ell\bar{\ell}$			32 ± 8	60 ± 19
$B_s \to \phi\,\ell\bar{\ell}$			62 ± 9	77 ± 10
$B_s \to \mu\bar{\mu}$				emerging
$\Lambda_b \to \Lambda\,\ell\bar{\ell}$			51 ± 7	
$B^+ \to \pi^+\,\ell\bar{\ell}$		limit		25 ± 7

- CP-averaged results
- vetoed q^2 region around J/ψ and ψ' resonances
- † unknown mixture of B^0 and $B^\pm$

Babar arXiv:1204.3933

Belle arXiv:0904.0770

CDF arXiv:1107.3753 + 1108.0695 + ICHEP 2012

LHCb LHCb-CONF-2012-008 (-003, -006), arXiv:1205.3422 + 1209.4284 + 1210.4492 + 1211.2674

Experimental data: $b \to s \ell^+ \ell^-$ – number of events

# of evts	BaBar 2012 471 M $\bar{B}B$	Belle 2009 605 fb^{-1}	CDF 2011 9.6 fb^{-1}	LHCb 2011/12 1 fb^{-1}
$B^0 \to K^{*0} \ell\bar{\ell}$	$137 \pm 44^\dagger$	$247 \pm 54^\dagger$	288 ± 20	900 ± 34
$B^+ \to K^{*+} \ell\bar{\ell}$			24 ± 6	76 ± 16
$B^+ \to K^+ \ell\bar{\ell}$	$153 \pm 41^\dagger$	$162 \pm 38^\dagger$	319 ± 23	1232 ± 40
$B^0 \to K^0_S \ell\bar{\ell}$			32 ± 8	60 ± 19
$B_s \to \phi \ell\bar{\ell}$			62 ± 9	77 ± 10
$B_s \to \mu\bar{\mu}$				emerging
$\Lambda_b \to \Lambda \ell\bar{\ell}$			51 ± 7	
$B^+ \to \pi^+ \ell\bar{\ell}$		limit		25 ± 7

- CP-averaged results
- vetoed q^2 region around J/ψ and ψ' resonances
- $\dagger$ unknown mixture of B^0 and $B^\pm$

Babar arXiv:1204.3933

Belle arXiv:0904.0770

CDF arXiv:1107.3753 + 1108.0695 + ICHEP 2012

LHCb LHCb-CONF-2012-008 (-003, -006), arXiv:1205.3422 + 1209.4284 + 1210.4492 + 1211.2674

Outlook / Prospects

Belle reprocessed all data 711 fb^{-1} $\to$ final analysis ?

LHCb end of 2012 additional $\gtrsim$ 2 fb^{-1} and $(5-7)$ fb^{-1} by the end of 2017

ATLAS / CMS pursue also analysis of $B \to K^* \mu\bar{\mu}$ and $B \to K \mu\bar{\mu}$

Belle II expects about (10-15) K events $B \to K^* \ell\bar{\ell}$ ($\gtrsim$ 2020) [A.J.Bevan arXiv:1110.3901]

Experimental data: $b \to s\,\ell^+\ell^-$ – number of events

# of evts	BaBar 2012 471 M $\bar{B}B$	Belle 2009 605 fb^{-1}	CDF 2011 9.6 fb^{-1}	LHCb 2011/12 1 fb^{-1}
$B^0 \to K^{*0}\,\ell\bar{\ell}$	$137 \pm 44^\dagger$	$247 \pm 54^\dagger$	288 ± 20	900 ± 34
$B^+ \to K^{*+}\,\ell\bar{\ell}$			24 ± 6	76 ± 16
$B^+ \to K^+\,\ell\bar{\ell}$	$153 \pm 41^\dagger$	$162 \pm 38^\dagger$	319 ± 23	1232 ± 40
$B^0 \to K_S^0\,\ell\bar{\ell}$			32 ± 8	60 ± 19
$B_s \to \phi\,\ell\bar{\ell}$			62 ± 9	77 ± 10
$B_s \to \mu\bar{\mu}$				emerging
$\Lambda_b \to \Lambda\,\ell\bar{\ell}$			51 ± 7	
$B^+ \to \pi^+\,\ell\bar{\ell}$		limit		25 ± 7

- CP-averaged results
- vetoed q^2 region around J/ψ and ψ' resonances
- † unknown mixture of B^0 and $B^\pm$

Babar arXiv:1204.3933

Belle arXiv:0904.0770

CDF arXiv:1107.3753 + 1108.0695 + ICHEP 2012

LHCb LHCb-CONF-2012-008 (-003, -006), arXiv:1205.3422 + 1209.4284 + 1210.4492 + 1211.2674

Outlook / Prospects

Belle	reprocessed all data 711 fb^{-1} $\to$ final analysis ?
LHCb	end of 2012 additional $\gtrsim$ 2 fb^{-1} and $(5-7)$ fb^{-1} by the end of 2017
ATLAS / CMS	pursue also analysis of $B \to K^*\mu\bar{\mu}$ and $B \to K\mu\bar{\mu}$
Belle II	expects about (10-15) K events $B \to K^*\ell\bar{\ell}$ ($\gtrsim$ 2020) [A.J.Bevan arXiv:1110.3901]

Angular analysis of $\overline{B} \to \overline{K}^* [\to \overline{K}\pi] + \ell^+\ell^-$

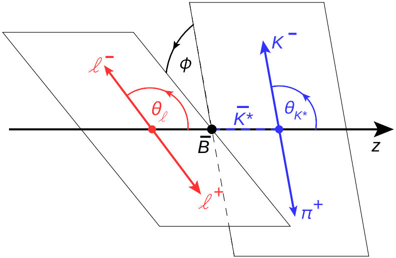
4-body decay with on-shell $\overline{K}^*$ (vector)

1) $q^2 = m^2_{\ell\bar{\ell}} = (p_\ell + p_{\bar{\ell}})^2 = (p_{\bar{B}} - p_{\bar{K}*})^2$

2) $\cos\theta_\ell$ with $\theta_\ell \angle(\vec{p}_{\bar{B}}, \vec{p}_\ell)$ in $(\ell\bar{\ell})$ – c.m. system

3) $\cos\theta_K$ with $\theta_K \angle(\vec{p}_{\bar{B}}, \vec{p}_{\bar{K}})$ in $(\bar{K}\pi)$ – c.m. system

4) ϕ $\angle(\vec{p}_{\bar{K}} \times \vec{p}_\pi, \vec{p}_{\bar{\ell}} \times \vec{p}_\ell)$ in B-RF



Angular analysis of $\overline{B} \to \overline{K}^* [\to \overline{K}\pi] + \ell^+\ell^-$

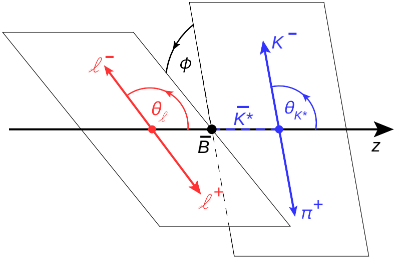
4-body decay with on-shell $\overline{K}^*$ (vector)

1) $q^2 = m^2_{\ell\bar{\ell}} = (p_\ell + p_{\bar{\ell}})^2 = (p_{\bar{B}} - p_{\bar{K}*})^2$

2) $\cos\theta_\ell$ with $\theta_\ell \angle(\vec{p}_{\bar{B}}, \vec{p}_\ell)$ in $(\ell\bar{\ell})$ – c.m. system

3) $\cos\theta_K$ with $\theta_K \angle(\vec{p}_{\bar{B}}, \vec{p}_{\bar{K}})$ in $(\bar{K}\pi)$ – c.m. system

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



$J_i(q^2)$ = "Angular Observables"

$$\frac{32\pi}{9} \frac{d^4\Gamma}{dq^2\, d\cos\theta_\ell\, d\cos\theta_K\, d\phi} = J_{1s} \sin^2\theta_K + J_{1c} \cos^2\theta_K + (J_{2s} \sin^2\theta_K + J_{2c} \cos^2\theta_K) \cos 2\theta_\ell$$

$$+ J_3 \sin^2\theta_K \sin^2\theta_\ell \cos 2\phi + J_4 \sin 2\theta_K \sin 2\theta_\ell \cos\phi + J_5 \sin 2\theta_K \sin\theta_\ell \cos\phi$$

$$+ (J_{6s} \sin^2\theta_K + J_{6c} \cos^2\theta_K) \cos\theta_\ell + J_7 \sin 2\theta_K \sin\theta_\ell \sin\phi$$

$$+ J_8 \sin 2\theta_K \sin 2\theta_\ell \sin\phi + J_9 \sin^2\theta_K \sin^2\theta_\ell \sin 2\phi$$

Angular analysis of $\overline{B} \to \overline{K}^* [\to \overline{K}\pi] + \ell^+\ell^-$

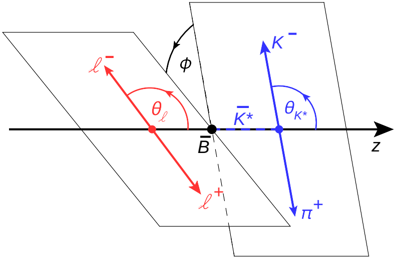
4-body decay with on-shell $\overline{K}^*$ (vector)

1) $q^2 = m^2_{\ell\bar{\ell}} = (p_\ell + p_{\bar{\ell}})^2 = (p_{\bar{B}} - p_{\bar{K}*})^2$

2) $\cos\theta_\ell$ with $\theta_\ell \angle(\vec{p}_{\bar{B}}, \vec{p}_\ell)$ in $(\ell\bar{\ell})$ – c.m. system

3) $\cos\theta_K$ with $\theta_K \angle(\vec{p}_{\bar{B}}, \vec{p}_{\bar{K}})$ in $(\bar{K}\pi)$ – c.m. system

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



$J_i(q^2)$ = "Angular Observables"

$$\frac{32\pi}{9} \frac{d^4\Gamma}{dq^2\, d\cos\theta_\ell\, d\cos\theta_K\, d\phi} = J_{1s}\sin^2\theta_K + J_{1c}\cos^2\theta_K + (J_{2s}\sin^2\theta_K + J_{2c}\cos^2\theta_K)\cos 2\theta_\ell$$
$$+ J_3 \sin^2\theta_K \sin^2\theta_\ell \cos 2\phi + J_4 \sin 2\theta_K \sin 2\theta_\ell \cos\phi + J_5 \sin 2\theta_K \sin\theta_\ell \cos\phi$$
$$+ (J_{6s}\sin^2\theta_K + J_{6c}\cos^2\theta_K)\cos\theta_\ell + J_7 \sin 2\theta_K \sin\theta_\ell \sin\phi$$
$$+ J_8 \sin 2\theta_K \sin 2\theta_\ell \sin\phi + J_9 \sin^2\theta_K \sin^2\theta_\ell \sin 2\phi$$

$\Rightarrow$ "$2 \times (12 + 12) = 48$" if measured separately: A) decay + CP-conj and B) for $\ell = e, \mu$

Angular analysis of $\overline{B} \to \overline{K}^* [\to \overline{K}\pi] + \ell^+\ell^-$

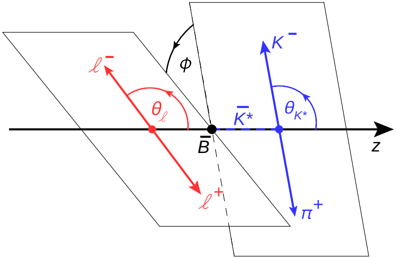
4-body decay with on-shell $\overline{K}^*$ (vector)

1) $q^2 = m^2_{\ell\bar{\ell}} = (p_\ell + p_{\bar{\ell}})^2 = (p_{\bar{B}} - p_{\bar{K}*})^2$

2) $\cos\theta_\ell$ with $\theta_\ell \angle(\vec{p}_{\bar{B}}, \vec{p}_\ell)$ in $(\ell\bar{\ell})$ – c.m. system

3) $\cos\theta_K$ with $\theta_K \angle(\vec{p}_{\bar{B}}, \vec{p}_{\bar{K}})$ in $(\bar{K}\pi)$ – c.m. system

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



CP-conj. decay $B^0 \to K^{*0}(\to K^+\pi^-)\ell^+\ell^-$: $d^4\bar{\Gamma}$ from $d^4\Gamma$ by replacing

$$\text{CP-even} \quad : \quad J_{1,2,3,4,7} \quad \longrightarrow \quad +\bar{J}_{1,2,3,4,7}[\delta_W \to -\delta_W]$$

$$\text{CP-odd} \quad : \quad J_{5,6,8,9} \quad \longrightarrow \quad -\bar{J}_{5,6,8,9}[\delta_W \to -\delta_W]$$

with weak phases δ_W conjugated

Angular analysis of $\overline{B} \to \overline{K}^* [\to \overline{K}\pi] + \ell^+\ell^-$

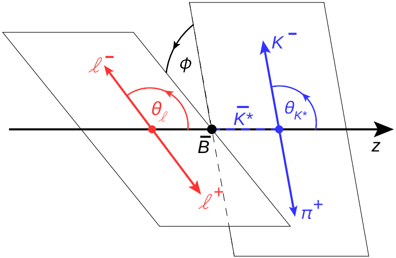
4-body decay with on-shell $\overline{K}^*$ (vector)

1) $q^2 = m^2_{\ell\bar{\ell}} = (p_\ell + p_{\bar{\ell}})^2 = (p_{\bar{B}} - p_{\bar{K}*})^2$

2) $\cos\theta_\ell$ with $\theta_\ell \angle(\vec{p}_{\bar{B}}, \vec{p}_\ell)$ in $(\ell\bar{\ell})$ – c.m. system

3) $\cos\theta_K$ with $\theta_K \angle(\vec{p}_{\bar{B}}, \vec{p}_{\bar{K}})$ in $(\bar{K}\pi)$ – c.m. system

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



CP-conj. decay $B^0 \to K^{*0}(\to K^+\pi^-)\ell^+\ell^-$: $d^4\bar{\Gamma}$ from $d^4\Gamma$ by replacing

$$\text{CP-even} \; : \; J_{1,2,3,4,7} \longrightarrow +\bar{J}_{1,2,3,4,7}[\delta_W \to -\delta_W]$$

$$\text{CP-odd} \; : \; J_{5,6,8,9} \longrightarrow -\bar{J}_{5,6,8,9}[\delta_W \to -\delta_W]$$

with weak phases δ_W conjugated

1) CP-odd : $A_{\text{CP}} \sim (J_i - \bar{J}_i) \sim d^4(\Gamma + \bar{\Gamma})$ = flavour-untagged B samples

2) (naive) T-odd $J_{7,8,9}$: $A_{\text{CP}} \sim \cos\delta_s \sin\delta_W \to$ not suppressed by small strong phases δ_s

Which operators contribute to which J_i ?

J_i	$SM^{(\prime)}$, $SM \times SM^{\prime}$	S	P	$SM^{(\prime)} \times (S,P)$	T,T5	$SM^{(\prime)} \times (T,T5)$	$(S,P) \times (T,T5)$
$1s$	1	–	–	–	1	m_ℓ	–
$1c$	1	1	1	m_ℓ/m_b	1	m_ℓ ($SM^{(\prime)} \times T5$)	–
$2s$	1	–	–	–	1	–	–
$2c$	1	–	–	–	1	–	–
3	1	–	–	–	1	–	–
4	1	–	–	–	1	–	–
5	1	–	–	m_ℓ	–	m_ℓ	$S \times T5$, $P \times T$
$6s$	1	–	–	–	–	m_ℓ	–
$6c$	–	–	–	m_ℓ	–	m_ℓ ($10^{(\prime)} \times T$)	$S \times T5$, $P \times T$
7	1	–	–	m_ℓ	–	m_ℓ	$P \times T5$, $S \times T$
8	1	–	–	–	$T \times T5$	–	–
9	1	–	–	–	$T \times T5$	–	–

[Krüger/Matias hep-ph/0502060], [Altmannshofer et al. arXiv:0811.1214v5], [Alok et al. 1008.2367, CB/Hiller/van Dyk 1212.2321]

–	=	no contribution
1	=	order one contribution
m_ℓ	=	kinematic suppression by lepton mass: $m_\ell/\sqrt{q^2}$

Naive factorization & narrow width approximation of $K^* \to K\pi$

Data for $B \to K^* + \ell^+\ell^-$: Br, $A_{\rm FB}$, F_L

angular analysis in each q^2-bin in θ_ℓ, θ_K

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_K} = \frac{3}{2}F_L\cos^2\theta_K + \frac{3}{4}(1 - F_L)\sin^2\theta_K$$

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

$\Rightarrow$ fitted F_L and $A_{\rm FB}$

Data for $B \to K^* + \ell^+\ell^-$: Br, $A_{\rm FB}$, F_L

angular analysis in each q^2-bin in θ_ℓ, θ_K

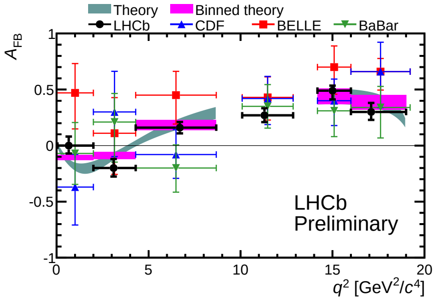
$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_K} = \frac{3}{2} F_L \cos^2\theta_K + \frac{3}{4}(1 - F_L)\sin^2\theta_K$$

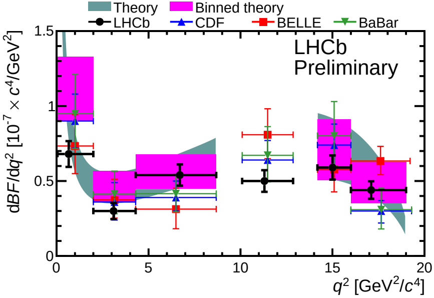
$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_\ell} = \frac{3}{4} F_L \sin^2\theta_\ell + \frac{3}{8}(1 - F_L)(1 + \cos^2\theta_\ell) + A_{\rm FB}\cos\theta_\ell$$

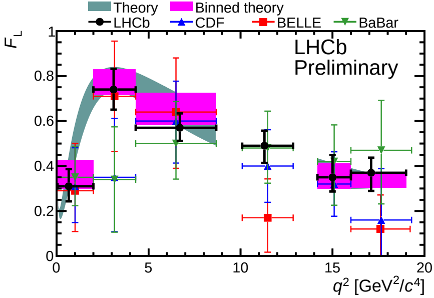
$\Rightarrow$ fitted F_L and $A_{\rm FB}$

SM-predictions: CB/Hiller/van Dyk arXiv:1105.0376

form factors Ball/Zwicky hep-ph/0412079







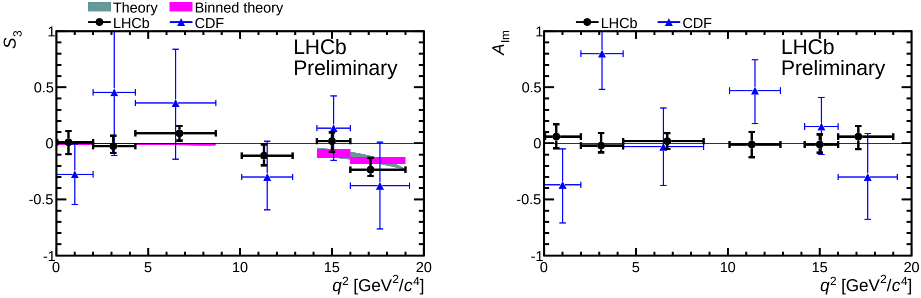
Data for $B \to K^* + \ell^+\ell^-$:

measurement of $A_T^{(2)}$, A_{im} from CDF and S_3, S_9 from LHCb

$$\frac{2\pi}{(\Gamma + \bar{\Gamma})} \frac{d(\Gamma + \bar{\Gamma})}{d\phi} = 1 + S_3 \cos 2\phi + (A_{im} \text{ or } S_9) \sin 2\phi$$

with

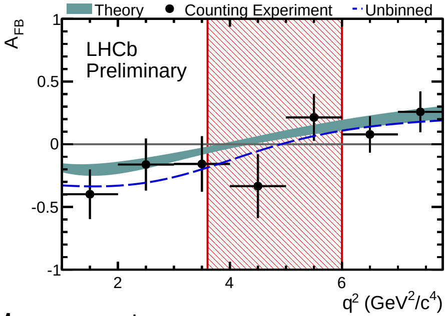
$$S_3 = \frac{J_3 + \bar{J}_3}{\Gamma + \bar{\Gamma}} = \frac{1}{2}(1 - F_L)\, A_T^{(2)}, \qquad A_{im} = A_9 = \frac{J_9 - \bar{J}_9}{\Gamma + \bar{\Gamma}}, \qquad S_9 = \frac{J_9 + \bar{J}_9}{\Gamma + \bar{\Gamma}},$$



Data for $B \to K^* + \ell^+\ell^-$:

Zero-crossing of $A_{\rm FB}$ in low-q^2 region:

finer q^2-bins than before: $\Delta q^2 = 1$ GeV^2



Measurement: [LHCb Collab. LHCb-CONF-2012-008]

$$q_0^2 = (4.9\,^{+1.1}_{-1.3})\ \text{GeV}^2$$

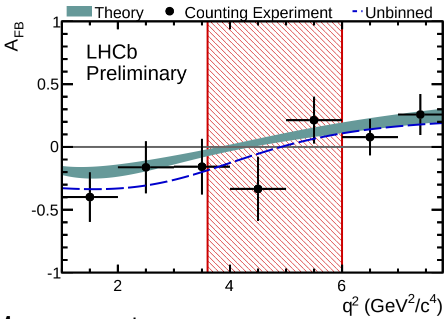
Theory (SM): $q_0^2 = (4.0 \ldots 4.3 \pm 0.3)$ GeV^2

[Beneke/Feldmann/Seidel hep-ph/0412400]
[Ali/Kramer/Zhu hep-ph/0601034]
[CB/Hiller/van Dyk/Wacker arXiv:1111.2558]

Data for $B \to K^* + \ell^+\ell^-$:

Zero-crossing of $A_{\rm FB}$ in low-q^2 region:

finer q^2-bins than before: $\Delta q^2 = 1$ GeV^2



Measurement: [LHCb Collab. LHCb-CONF-2012-008]

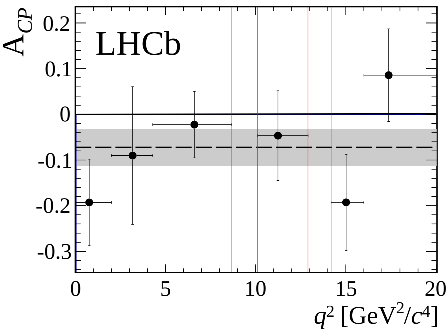
$$q_0^2 = (4.9\,^{+1.1}_{-1.3})\ \text{GeV}^2$$

Theory (SM): $q_0^2 = (4.0 \ldots 4.3 \pm 0.3)$ GeV^2

[Beneke/Feldmann/Seidel hep-ph/0412400]
[Ali/Kramer/Zhu hep-ph/0601034]
[CB/Hiller/van Dyk/Wacker arXiv:1111.2558]

Rate CP asymmetry $A_{\rm CP}$

[LHCb Collaboration arXiv:1210.4492]



$B \to K^*(\to K\pi) + \ell^+\ell^-$ and S-wave:

Theorists assume P-wave K^{*0} (+ narrow-width approx.) decaying in $(K\pi)$-final state ...

... BUT in reality: resonant and non-resonant production of $(K\pi)$ in S-wave config for $(K\pi)$-inv. mass $\sqrt{p^2}$ around $M_{K*} \approx 892$ MeV (D-wave contr. from $K^{*0}(1430)$ negligible for $\sqrt{p^2} < 1.2$ GeV)

$B \to K^*(\to K\pi) + \ell^+\ell^-$ and S-wave:

Theorists assume P-wave K^{*0} (+ narrow-width approx.) decaying in $(K\pi)$-final state ...

... BUT in reality: resonant and non-resonant production of $(K\pi)$ in S-wave config for $(K\pi)$-inv. mass $\sqrt{p^2}$ around $M_{K*} \approx 892$ MeV (D-wave contr. from $K^{*0}(1430)$ negligible for $\sqrt{p^2} < 1.2$ GeV)

Modification of angular observables J_i due to S-wave

$i = 3, 6, 9$	not affected		
$i = 4, 5, 7, 8$	$J_i \sin 2\theta_K$	$\to$	$J_i \sin 2\theta_K + \mathcal{J}_i \sin\theta_K$
$i = 1s, 1c, 2s, 2c$	$J_{is} \sin^2\theta_K + J_{ic} \cos^2\theta_K$	$\to$	$(J_{is} + \mathcal{J}_{is}) \sin^2\theta_K + (J_{ic} + \mathcal{J}_{ic}) \cos^2\theta_K$ $+\mathcal{J}_{isc} \cos\theta_K$

[Lu/Wang arXiv:1111.1513, Becirevic/Tayduganov 1207.4004, Blake/Egede/Shires 1210.5279, Matias 1209.1525]

$\Rightarrow$ $\mathcal{J}_{4,5,7,8,1sc,2sc}$: interference of S- and P-wave, can be separated by angular analysis

$\Rightarrow$ $\mathcal{J}_{1s,1c,2s,2c}$: pure S-wave, must be measured in $\sqrt{p^2}$ sidebands around M_{K*}

S-wave contribution in $B^0 \to J/\psi K^+\pi^- \approx 7\%$ for 0.8 GeV $< \sqrt{p^2} < 1.0$ GeV [BaBar hep-ex:0411016]
$\Rightarrow$ no information yet on $B^0 \to K^+\pi^-\ell^+\ell^-$

$B \to K^*(\to K\pi) + \ell^+\ell^-$ and S-wave:

Theorists assume P-wave K^{*0} (+ narrow-width approx.) decaying in $(K\pi)$-final state ...

... BUT in reality: resonant and non-resonant production of $(K\pi)$ in S-wave config for $(K\pi)$-inv. mass $\sqrt{p^2}$ around $M_{K*} \approx 892$ MeV (D-wave contr. from $K^{*0}(1430)$ negligible for $\sqrt{p^2} < 1.2$ GeV)

Inclusion of S-wave in angular analysis

[Blake/Egede/Shires arXiv:1210.5279]

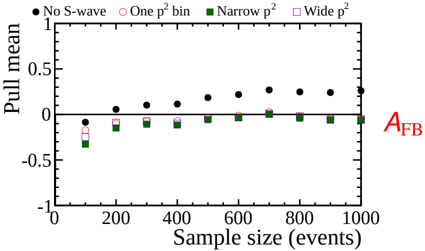
$\Rightarrow$ based on toy samples, modeling S-wave $\sqrt{p^2}$-dep. using LASS-parametrisation
[LASS Collab. NPB296 (1987) 493]

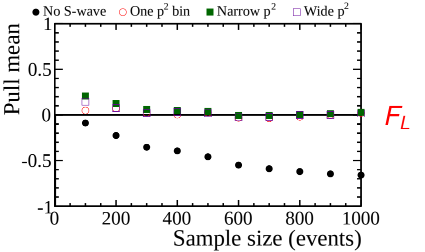
$\Rightarrow$ Pull mean after refitting observable from toy sample depending on sample size (in given q^2-bin) when

a) ignoring S-wave

b) for different treatment of $\sqrt{p^2}$-dependence

$\Rightarrow$ "Inclusion of S-wave component will be mandatory in future experiments"



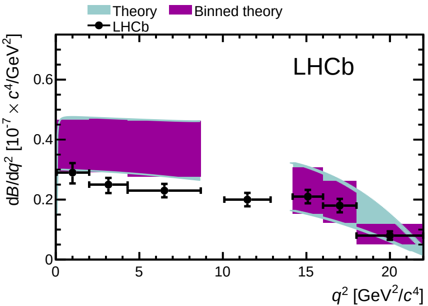


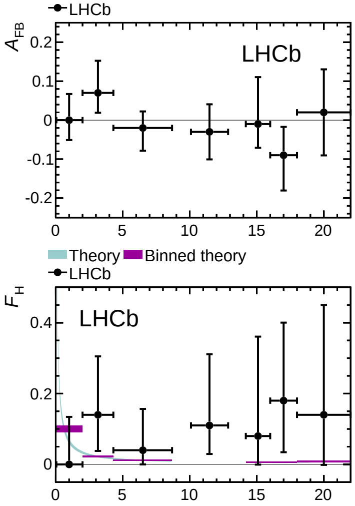
$B \to K + \ell^+\ell^-$: 3-body decay → 2 kinematic variables: q^2, θ_ℓ

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

$B \to K + \ell^+\ell^-$: 3-body decay → 2 kinematic variables: q^2, θ_ℓ

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





LHCb arXiv:1209.4284 : $\langle Br \rangle$, $\langle A_{FB} \rangle$, $\langle F_H \rangle$

and previous results for $\langle Br \rangle$ from Belle arXiv:0904.0770
CDF arXiv:1107.3753
BaBar arXiv:1204.3933

SM predicition: CB/Hiller/van Dyk/Wacker arXiv:1111.2558
form factors from Khodjamirian et al. arXiv:1006.4945

$B_s \to \mu^+\mu^-$

SM prediction: $Br[B_s \to \mu^+\mu^-] \approx 3.5 \times 10^{-9}$ [De Bruyn et al. arXiv:1204.1737]

time-integrated accounting for B_s-mixing

$B_s \to \mu^+\mu^-$

SM prediction: $Br[B_s \to \mu^+\mu^-] \approx 3.5 \times 10^{-9}$ [De Bruyn et al. arXiv:1204.1737]

time-integrated accounting for B_s-mixing

Beyond SM: $$Br \sim |C_S - C'_S|^2 + \left|(C_P - C'_P) + \frac{2m_\ell}{m_{B_s}}(C_{10} - C'_{10})\right|^2$$

$B_s \to \mu^+\mu^-$

SM prediction: $Br[B_s \to \mu^+\mu^-] \approx 3.5 \times 10^{-9}$ [De Bruyn et al. arXiv:1204.1737]

time-integrated accounting for B_s-mixing

Beyond SM:

$$Br \sim |C_S - C_S'|^2 + \left|(C_P - C_P') + \frac{2m_\ell}{m_{B_s}}(C_{10} - C_{10}')\right|^2$$

- since $\sim$ 10 years CDF and DØ lowered upper bound from:

  $$\mathcal{O}(10^{-6}) \to \mathcal{O}(10^{-8})$$

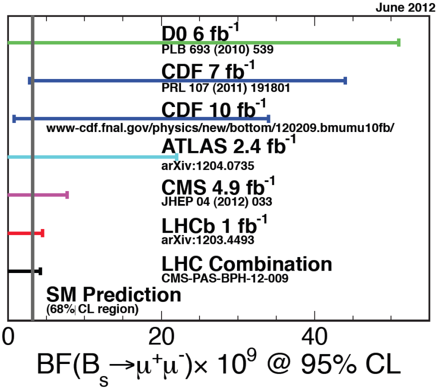
- nowadays measurements from: CDF, DØ, LHCb, ATLAS and CMS

  $\Rightarrow$ LHCb finds signal with 3.5σ

  $$Br = (3.2^{+1.5}_{-1.2}) \times 10^{-9}$$

  based on 2.1 fb^{-1}

  [LHCb Collaboration arXiv:1211.2674]

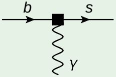


Exclusive decays

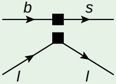
– $B \to K^*(\to K\pi)\,\ell^+\ell^-$ –

Hadronic amplitude $B \to K^* (\to K\pi)\, \ell^+ \ell^-$ neglecting 4-quark operators

$$\mathcal{M} = \langle K\pi|\; C_7 \times$$



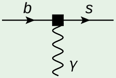
$$+ \; C_{9,10} \times$$

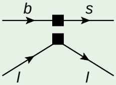


$$|B\rangle$$

Exclusive $B \to K^*(\to K\pi)\,\ell^+\ell^-$

Hadronic amplitude $B \to K^*(\to K\pi)\,\ell^+\ell^-$ — neglecting 4-quark operators

$\mathcal{M} = \langle K\pi |\ C_7 \times$ 

$+\ C_{9,10} \times$ 

$| B \rangle$

$\mathcal{M}$ may expressed in terms of transversity amplitudes of K^* ($m_\ell = 0$)

. . . using narrow width approximation & intermediate K^* on-shell

$\Rightarrow$ "just" requires $B \to K^*$ form factors V, $A_{1,2}$, $T_{1,2,3}$:

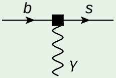
$$A_\perp^{L,R} \sim \sqrt{2\,\lambda}\left[(C_9 \mp C_{10})\frac{V}{M_B + M_{K*}} + \frac{2\,m_b}{q^2} C_7\, T_1\right],$$

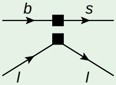
$$A_\parallel^{L,R} \sim -\sqrt{2}\,(M_B^2 - M_{K*}^2)\left[(C_9 \mp C_{10})\frac{A_1}{M_B - M_{K*}} + \frac{2\,m_b}{q^2} C_7\, T_2\right],$$

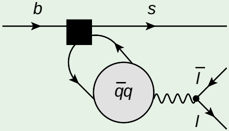
$$A_0^{L,R} \sim -\frac{1}{2\,M_{K*}\sqrt{q^2}}\left\{(C_9 \mp C_{10})\Big[\ldots A_1 + \ldots A_2\Big] + 2\,m_b C_7\Big[\ldots T_2 + \ldots T_3\Big]\right\}$$

Exclusive $B \to K^*(\to K\pi)\,\ell^+\ell^-$

Hadronic amplitude $B \to K^*(\to K\pi)\,\ell^+\ell^-$ — including 4-quark operators

$\mathcal{M} = \langle K\pi|\; C_7 \times$ 

$+ \; C_{9,10} \times$ 

$+ \sum_i C_i \times$ 

$|B\rangle$

... but 4-Quark operators and $\mathcal{O}_{8g}$ have to be included

- current-current $b \to s + (\bar{u}u,\, \bar{c}c)$
- QCD-penguin operators $b \to s + \bar{q}q$ ($q = u, d, s, c, b$)

$\Rightarrow$ large peaking background around certain $q^2 = (M_{J/\psi})^2,\, (M_{\psi'})^2$:

$B \to K^{(*)}(\bar{q}q) \to K^{(*)}\bar{\ell}\ell$

q^2 - regions in $b \to s\,\ell^+\ell^-$

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

$\Rightarrow$ Two regions in q^2 where theory can give reliable predictions beyond naive factorization

q^2-region	low-q^2: $q^2 \ll M_B^2$	high-q^2: $q^2 \sim M_B^2$
$K^{(*)}$-recoil	large recoil: $E_{K^{(*)}} \sim M_B/2$	low recoil: $E_{K^{(*)}} \sim M_{K^{(*)}} + \Lambda_{\rm QCD}$
theory method	QCDF, nl OPE: $q^2 \in [1, 6]$ GeV^2	OPE + HQET: $q^2 \gtrsim (14\ldots15)$ GeV^2

[QCDF: Beneke/Feldmann/Seidel hep-ph/0106067, hep-ph/0412400]
[non-local OPE: Khodjamirian/Mannel/Pivovarov/Wang arXiv:1006.4945 & 1211.0234]
[local OPE: Grinstein/Pirjol hep-ph/0404250; Beylich/Buchalla/Feldmann arXiv:1101.5118]

$\Rightarrow$ $\bar{c}c$ vetoed in experiment

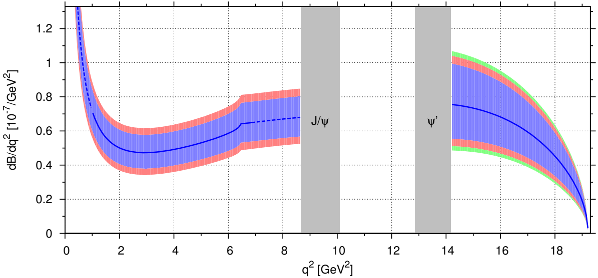
$\mathrm{d}Br[B \to K^*\ell^+\ell^-]/\mathrm{d}q^2$

$\Rightarrow$ light resonances $q^2 \lesssim 1$ GeV^2 not vetoed

small for CP-aver. obs's
relevant for CP-asy's

[Jäger/Martin-Camalich 1212.2263]

[Khodjamirian/Mannel/Wang 1211.0234]



Low-q^2 = Large Recoil

QCD Factorisation (QCDF)

[Beneke/Feldmann/Seidel hep-ph/0106067, hep-ph/0412400]

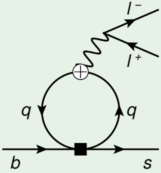
= (large recoil + heavy quark) limit [also Soft Collinear ET (SCET)]

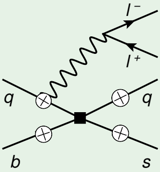
$$\left\langle \bar{\ell}\ell\, K_a^* \,\middle|\, H_{\rm eff}^{(i)} \,\middle|\, B \right\rangle \sim$$

$$C_a^{(i)} \times \xi_a + \phi_B \otimes T_a^{(i)} \otimes \phi_{a,K*} + \mathcal{O}(\Lambda_{\rm QCD}/m_b)$$

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

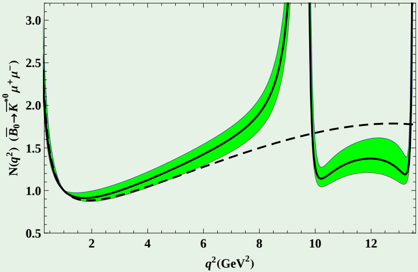
ϕ_B, $\phi_{a,K*}$: B– and K_a^*–distribution amplitudes





$c\bar{c}$-contributions

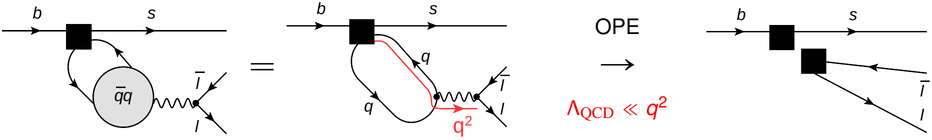
[Khodjamirian/Mannel/Pivovarov/Wang arXiv:1006.4945]



- OPE near light-cone incl. soft-gluon emission (non-local operator) for $q^2 \leqslant 4$ GeV^2 $\ll 4m_c^2$
- hadronic dispersion relation using measured $B \to K^{(*)}(\bar{c}c)$ amplitudes at $q^2 \geqslant 4$ GeV^2
- $B \to K^{(*)}$ form factors from LCSR
- up to (15-20) % in rate for $1 < q^2 < 6$ GeV^2

High-q^2 = Low Recoil

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 $V, A_{0,1,2}, T_{1,2,3}$

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

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

High-q^2 = Low Recoil

[Beylich/Buchalla/Feldmann arXiv:1101.5118]

$dim = 3$ 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 $(\Lambda_{\rm QCD}/m_b)^2 \sim 2$ %,
explicite estimate @ $q^2 = 15$ GeV^2: < 1%

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

beyond OPE duality violating effects

- based on Shifman model for c-quark correlator + fit to recent BES data
- ± 2 % for integrated rate $q^2 > 15$ GeV^2

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

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

Main theory uncertainty: form factors (FF)

Currently, FF only known from LCSR @ low q^2

$\Rightarrow$ @ high q^2 only extrapolations based on some q^2-dependence

- pole approximations [Ball/Zwicky hep-ph/0406232 + 0412079]
- series expansion (z-expansion) [Bharucha/Feldmann/Wick arXiv:1004.3249]
  [Khodjamirian/Mannel/Pivovavrov/Wang arXiv:1006.4945]

Main theory uncertainty: form factors (FF)

Currently, FF only known from LCSR @ low q^2

$\Rightarrow$ @ high q^2 only extrapolations based on some q^2-dependence

- pole approximations [Ball/Zwicky hep-ph/0406232 + 0412079]
- series expansion (z-expansion) [Bharucha/Feldmann/Wick arXiv:1004.3249]

[Khodjamirian/Mannel/Pivovavrov/Wang arXiv:1006.4945]

@ high q^2: Lattice QCD required to use observables like Br, A_{FB}, F_L, F_H, ...

$\Rightarrow$ work in progress

- $B \to K$ [Zhou et al. arXiv:1111.0981, Bouchard et al. arXiv:1210.6992]
- $B \to K^*$ [Liu et al. arXiv:1101.2726]

($B \to K$ technically easier on lattice,
$B \to K^*$ systematically limited $\to$ need to solve problem of unstable K^* on lattice)

Optimised observables in $B \to K^*(\to K\pi)\,\ell^+\ell^-$

Angular observables

$$J_i(q^2) \sim \{\mathrm{Re}, \mathrm{Im}\} \left[A_m^{L,R} \left(A_n^{L,R} \right)^* \right]$$

$$\sim \sum_a (C_a F_a) \sum_b (C_b F_b)^*$$

$A_m^{L,R} \ldots K^*$-transversity amplitudes $m = \perp, \parallel, 0$

$C_a \ldots$ short-distance coefficients

$F_a \ldots$ form factors

Angular observables

$$J_i(q^2) \sim \{\text{Re, Im}\} \left[A_m^{L,R} \left(A_n^{L,R} \right)^* \right]$$

$$\sim \sum_a (C_a F_a) \sum_b (C_b F_b)^*$$

$A_m^{L,R} \ldots K^*$-transversity amplitudes $m = \perp, \|, 0$

$C_a \ldots$ short-distance coefficients

$F_a \ldots$ form factors

simplify when using form factor relations:

low K^* recoil limit: $E_{K*} \sim M_{K*} \sim \Lambda_{\rm QCD}$ [Isgur/Wise PLB232 (1989) 113, PLB237 (1990) 527]

$$T_1 \approx V, \qquad T_2 \approx A_1, \qquad T_3 \approx A_2 \frac{M_B^2}{q^2}$$

large K^* recoil limit: $E_{K*} \sim M_B$ [Charles et al. hep-ph/9812358, Beneke/Feldmann hep-ph/0008255]

$$\xi_\perp \equiv \frac{M_B}{M_B + M_{K*}} V \approx \frac{M_B + M_{K*}}{2E_{K*}} A_1 \approx T_1 \approx \frac{M_B}{2E_{K*}} T_2$$

$$\xi_\| \equiv \frac{M_B + M_{K*}}{2E_{K*}} A_1 - \frac{M_B - M_{K*}}{M_{K*}} A_2 \approx \frac{M_B}{2E_{K*}} T_2 - T_3$$

Sub-leading corrections to TransAmp's

$\lambda = \Lambda_{\rm QCD}/m_b \sim 0.15$

Low hadronic recoil

$$A_i^{L,R} \sim C^{L,R} \times f_i \qquad C^{L,R} = (C_9 \mp C_{10}) + \kappa \frac{2m_b^2}{q^2} C_7,$$

1 SD-coefficient $C^{L,R}$ and 3 FF's f_i ($i = \perp, \parallel, 0$)

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

("helicity FF's" [Bharucha/Feldmann/Wick arXiv:1004.3249])

Sub-leading corrections to TransAmp's

$\lambda = \Lambda_{\text{QCD}}/m_b \sim 0.15$

Low hadronic recoil

FF symmetry breaking

$$A_i^{L,R} \sim C^{L,R} \times f_i + C_7 \times \mathcal{O}(\lambda, \alpha_s)$$

$$C^{L,R} = (C_9 \mp C_{10}) + \kappa \frac{2m_b^2}{q^2} C_7,$$

1 SD-coefficient $C^{L,R}$ and 3 FF's f_i ($i = \perp, \|, 0$)

$C_7^{\text{SM}} \approx -0.3, \; C_9^{\text{SM}} \approx 4.2, \; C_{10}^{\text{SM}} \approx -4.2$

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

("helicity FF's" [Bharucha/Feldmann/Wick arXiv:1004.3249])

Sub-leading corrections to TransAmp's

$\lambda = \Lambda_{\rm QCD}/m_b \sim 0.15$

Low hadronic recoil

FF symmetry breaking   OPE

$$A_i^{L,R} \sim C^{L,R} \times f_i + C_7 \times \mathcal{O}(\lambda, \alpha_s) + \mathcal{O}\left(\lambda^2\right), \qquad C^{L,R} = (C_9 \mp C_{10}) + \kappa \frac{2m_b^2}{q^2} C_7,$$

1 SD-coefficient $C^{L,R}$ and 3 FF's f_i ($i = \perp, \parallel, 0$) $C_7^{\rm SM} \approx -0.3,\ C_9^{\rm SM} \approx 4.2,\ C_{10}^{\rm SM} \approx -4.2$

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

("helicity FF's" [Bharucha/Feldmann/Wick arXiv:1004.3249])

Sub-leading corrections to TransAmp's

$\lambda = \Lambda_{\rm QCD}/m_b \sim 0.15$

Low hadronic recoil

$\Rightarrow$ small, apart from possible duality violations

FF symmetry breaking   OPE

$$A_i^{L,R} \sim C^{L,R} \times f_i + C_7 \times \mathcal{O}(\lambda, \alpha_s) + \mathcal{O}\left(\lambda^2\right), \qquad C^{L,R} = (C_9 \mp C_{10}) + \kappa \frac{2m_b^2}{q^2} C_7,$$

1 SD-coefficient $C^{L,R}$ and 3 FF's f_i ($i = \perp, \parallel, 0$)

$C_7^{\rm SM} \approx -0.3,\; C_9^{\rm SM} \approx 4.2,\; C_{10}^{\rm SM} \approx -4.2$

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

("helicity FF's" [Bharucha/Feldmann/Wick arXiv:1004.3249])

Large hadronic recoil

$$A_{\perp,\parallel}^{L,R} \sim \pm C_\perp^{L,R} \times \xi_\perp + \mathcal{O}(\alpha_s, \lambda), \qquad A_0^{L,R} \sim C_\parallel^{L,R} \times \xi_\parallel + \mathcal{O}(\alpha_s, \lambda)$$

2 SD-coefficients $C_{\perp,\parallel}^{L,R}$ and 2 FF's $\xi_{\perp,\parallel}$

$$C_\perp^{L,R} = (C_9 \mp C_{10}) + \frac{2m_b M_B}{q^2} C_7, \qquad C_\parallel^{L,R} = (C_9 \mp C_{10}) + \frac{2\,m_b}{M_B} C_7,$$

Sub-leading corrections to TransAmp's

$\lambda = \Lambda_{\rm QCD}/m_b \sim 0.15$

Low hadronic recoil

$\Rightarrow$ small, apart from possible duality violations

FF symmetry breaking   OPE

$$A_i^{L,R} \sim C^{L,R} \times f_i + C_7 \times \mathcal{O}(\lambda, \alpha_s) + \mathcal{O}\left(\lambda^2\right), \qquad C^{L,R} = (C_9 \mp C_{10}) + \kappa \frac{2m_b^2}{q^2} C_7,$$

1 SD-coefficient $C^{L,R}$ and 3 FF's f_i ($i = \perp, \parallel, 0$)

$C_7^{\rm SM} \approx -0.3,\ C_9^{\rm SM} \approx 4.2,\ C_{10}^{\rm SM} \approx -4.2$

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

("helicity FF's" [Bharucha/Feldmann/Wick arXiv:1004.3249])

Large hadronic recoil

$\Rightarrow$ limited, end-point-divergences at $\mathcal{O}(\lambda)$

$$A_{\perp,\parallel}^{L,R} \sim \pm C_\perp^{L,R} \times \xi_\perp + \mathcal{O}(\alpha_s, \lambda), \qquad A_0^{L,R} \sim C_\parallel^{L,R} \times \xi_\parallel + \mathcal{O}(\alpha_s, \lambda)$$

2 SD-coefficients $C_{\perp,\parallel}^{L,R}$ and 2 FF's $\xi_{\perp,\parallel}$

$$C_\perp^{L,R} = (C_9 \mp C_{10}) + \frac{2 m_b M_B}{q^2} C_7, \qquad C_\parallel^{L,R} = (C_9 \mp C_{10}) + \frac{2\, m_b}{M_B} C_7,$$

"Optimized observables" in $B \to K^* \ell^+ \ell^-$

Not yet measured (except $A_T^{(2)}$) !!!

Idea: reduce form factor (FF) sensitivity by combination (usually ratios) of angular obs's J_i

$\Rightarrow$ guided by large energy limit @ low-q^2 and Isgur-Wise @ high-q^2 FF-relations

"Optimized observables" in $B \to K^* \ell^+ \ell^-$

Not yet measured (except $A_T^{(2)}$) !!!

Idea: reduce form factor (FF) sensitivity by combination (usually ratios) of angular obs's J_i

$\Rightarrow$ guided by large energy limit @ low-q^2 and Isgur-Wise @ high-q^2 FF-relations

@ low-q^2 = large recoil

$$A_T^{(2)} = P_1 = \frac{J_3}{2\, J_{2s}}, \qquad A_T^{(\mathrm{re})} = 2\, P_2 = \frac{J_{6s}}{4\, J_{2s}}, \qquad A_T^{(\mathrm{im})} = -2\, P_3 = \frac{J_9}{2\, J_{2s}},$$

$$H_T^{(1)} = P_4 = \frac{\sqrt{2} J_4}{\sqrt{-J_{2c}(2J_{2s} - J_3)}}, \qquad H_T^{(2)} = P_5 = \frac{J_5/\sqrt{2}}{\sqrt{-J_{2c}(2J_{2s} + J_3)}},$$

$$P_6 = \frac{-J_7/\sqrt{2}}{\sqrt{-J_{2c}(2J_{2s} - J_3)}}, \qquad A_T^{(3)} = \sqrt{\frac{(2\, J_4)^2 + J_7^2}{-2\, J_{2c}\, (2\, J_{2s} + J_3)}}, \qquad A_T^{(4)} = \sqrt{\frac{J_5^2 + (2\, J_8)^2}{(2\, J_4)^2 + J_7^2}}$$

[Krüger/Matias hep-ph/0502060, Egede/Hurth/Matias/Ramon/Reece arXiv:0807.2589 + 1005.0571]

[CB/Hiller/van Dyk arXiv:1006.5013]

[Becirevic/Schneider arXiv:1106.3283]

[Matias/Mescia/Ramon/Virto arXiv:1202.4266]

"Optimized observables" in $B \to K^* \ell^+ \ell^-$

Not yet measured (except $A_T^{(2)}$) !!!

Idea: reduce form factor (FF) sensitivity by combination (usually ratios) of angular obs's J_i

$\Rightarrow$ guided by large energy limit @ low-q^2 and Isgur-Wise @ high-q^2 FF-relations

@ high-q^2 = low recoil

$$H_T^{(1)} = P_4 = \frac{\sqrt{2} J_4}{\sqrt{-J_{2c}(2J_{2s} - J_3)}},$$

$$H_T^{(2)} = P_5 = \frac{J_5/\sqrt{2}}{\sqrt{-J_{2c}(2J_{2s} + J_3)}}, \qquad H_T^{(3)} = \frac{J_{6s}/2}{\sqrt{(2J_{2s})^2 - (J_3)^2}},$$

$$H_T^{(4)} = Q = \frac{\sqrt{2} J_8}{\sqrt{-J_{2c}(2J_{2s} + J_3)}}, \qquad H_T^{(5)} = \frac{-J_9}{\sqrt{(2J_{2s})^2 - (J_3)^2}},$$

$$\frac{A_{im}}{A_{\rm FB}} = \frac{J_9}{J_{6s}}, \qquad \text{and} \qquad \frac{J_8}{J_5}$$

[CB/Hiller/van Dyk arXiv:1006.5013]
[Matias/Mescia/Ramon/Virto arXiv:1202.4266 + 1207.2753]
[CB/Hiller/van Dyk arXiv:1212.2321]

(A_{im} already measured by CDF, but large uncertainty)

Optimized observables $B \to K^* \ell^+ \ell^-$ @ low q^2 ...

... experiments provide only $A_{\rm FB}$, F_L, S_3, however optimized observables related as:

$$A_T^{(2)} = P_1 = \frac{2\, S_3}{1 - F_L}, \qquad\qquad A_T^{(re)} = 2 P_2 = -\frac{4}{3} \frac{A_{\rm FB}}{(1 - F_L)}$$

convert $A_{\rm FB}$, F_L, $S_3 \to P_1$, P_2 [Descotes-Genon/Matias/Ramon/Virto arXiv:1207.2753]

in q^2-bins: [2, 4.3] and [4.3, 8.68] GeV^2 (naive theorist conversion due to lacking correlations)

Optimized observables $B \to K^* \ell^+ \ell^-$ @ low q^2 ...

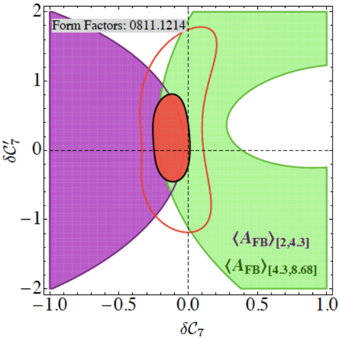
... experiments provide only $A_{\rm FB}$, F_L, S_3, however optimized observables related as:

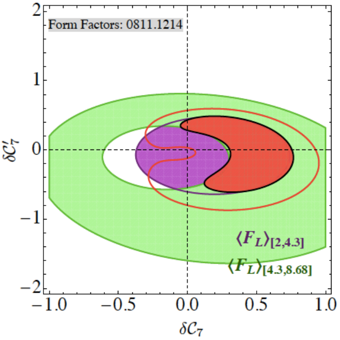
$$A_T^{(2)} = P_1 = \frac{2\, S_3}{1 - F_L}, \qquad\qquad A_T^{(re)} = 2 P_2 = -\frac{4}{3} \frac{A_{\rm FB}}{(1 - F_L)}$$

convert $A_{\rm FB}$, F_L, $S_3 \to P_1$, P_2 [Descotes-Genon/Matias/Ramon/Virto arXiv:1207.2753]

in q^2-bins: [2, 4.3] and [4.3, 8.68] GeV^2 (naive theorist conversion due to lacking correlations)

in $\delta C_7 - \delta C_{7'}$ plane $A_{\rm FB}$ and F_L





Optimized observables $B \to K^* \ell^+\ell^-$ @ low q^2 ...

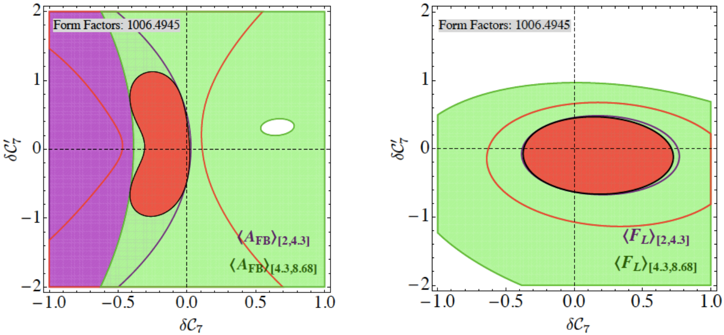
... experiments provide only $A_{\rm FB}$, F_L, S_3, however optimized observables related as:

$$A_T^{(2)} = P_1 = \frac{2\,S_3}{1-F_L}, \qquad A_T^{(re)} = 2P_2 = -\frac{4}{3}\frac{A_{\rm FB}}{(1-F_L)}$$

convert $A_{\rm FB}$, F_L, $S_3 \to P_1$, P_2 [Descotes-Genon/Matias/Ramon/Virto arXiv:1207.2753]

in q^2-bins: [2, 4.3] and [4.3, 8.68] GeV^2 (naive theorist conversion due to lacking correlations)

in $\delta C_7 - \delta C_{7'}$ plane $A_{\rm FB}$ and F_L



Optimized observables $B \to K^* \ell^+ \ell^-$ @ low q^2 …

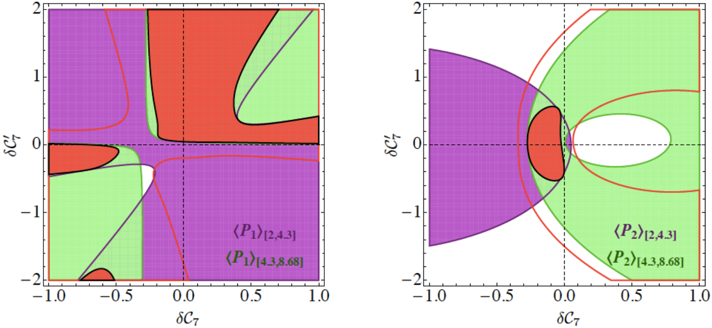
… experiments provide only $A_{\rm FB}$, F_L, S_3, however optimized observables related as:

$$A_T^{(2)} = P_1 = \frac{2\, S_3}{1 - F_L}, \qquad A_T^{(re)} = 2P_2 = -\frac{4}{3}\frac{A_{\rm FB}}{(1 - F_L)}$$

convert $A_{\rm FB}$, F_L, $S_3 \to P_1$, P_2 [Descotes-Genon/Matias/Ramon/Virto arXiv:1207.2753]

in q^2-bins: [2, 4.3] and [4.3, 8.68] GeV^2 (naive theorist conversion due to lacking correlations)

in $\delta C_7 - \delta C_{7'}$ plane P_1 and P_2



$A_{\rm FB}$ and F_L are sensitive to form factors, P_1 and P_2 not!

OPE predictions @ high-q^2 beyond SM

[CB/Hiller/van Dyk arXiv:1212.2321]

Scenario	$\lvert H_T^{(1)}\rvert = 1$	$H_T^{(2)} = H_T^{(3)}$	$H_T^{(4)} = H_T^{(5)}$	$J_{6c} = 0$	$J_7 = 0$	$J_{8,9} = 0$
SM	✓	✓	✓	✓	✓	✓
SM + (S+P)	✓	$\frac{m_\ell}{Q}\,\Re C_{79}\Delta_S^*$	✓	$\frac{m_\ell}{Q}\,\Re C_{79}\Delta_S^*$	$\frac{m_\ell}{Q}\,\Im C_{79}\Delta_S^*$	✓
SM + (T+T5)	$\frac{M_{K*}^2}{Q^2}\,\rho_1^T$	$\frac{m_\ell}{Q}\,\Re C_{10}C_{T(T5)}^*$	$\frac{M_{K*}}{Q}\,\Im\rho_2^T$	$\frac{m_\ell}{Q}\,\Re C_{10}C_T^*$	$\frac{m_\ell}{Q}\,\Im C_{10}C_{T5}^*$	$\Im\rho_2^T$
SM + SM'	✓	✓	✓	✓	✓	$\Im\rho_2$
all	$\frac{M_{K*}^2}{Q^2}\,\rho_1^T$	$\Re C_{T(T5)}\Delta_{P(S)}^*$	$\frac{M_{K*}}{Q}\,\Im\rho_2^{(T)}$	$\Re C_{T(T5)}\Delta_{P(S)}^*$	$\Im C_{T(T5)}\Delta_{S(P)}^*$	$\Im\rho_2^{(T)}$

Low recoil relations predicted by OPE

- SM-like models (first row) and the leading terms that break them in SM extensions
- ✓= at most corrections of order $\alpha_s\,\Lambda/m_b$ and $\mathcal{C}_7/\mathcal{C}_9\,\Lambda/m_b$
- $Q = \mathcal{O}(m_b, \sqrt{q^2})$ and $\Delta_{S,P} \equiv (C_{S,P} - C_{S',P'})$

⇒ if too large violations were measured this would imply contributions beyond OPE

with current data, tensor operators are constraint such that $\left|\,|H_T^{(1)}| - 1\right| \lesssim 0.08$

Fits and implications

– Model-independent –

"Global Fit" = combination of $b \to s + (\gamma, \ell^+\ell^-)$ observables

Parameters of interest

$$\vec{\theta} = (C_i)$$

"Global Fit" = combination of $b \to s + (\gamma, \ell^+\ell^-)$ observables

Parameters of interest

$$\vec{\theta} = (C_i)$$

Nuisance parameters

$\vec{\nu}$

1) process-specific

FF's, decay const's,
LCDA pmr's,
sub-leading Λ/m_b,
renorm. scales: $\mu_{b,0}$

2) general

quark masses, CKM, ...

“Global Fit” = combination of $b \to s + (\gamma,\ \ell^+\ell^-)$ observables

Parameters of interest

$$\vec{\theta} = (C_i)$$

Nuisance parameters

$\vec{\nu}$

1) process-specific

FF’s, decay const’s,
LCDA pmr’s,
sub-leading Λ/m_b,
renorm. scales: $\mu_{b,0}$

2) general

quark masses, CKM, . . .

Observables

1) observables

$$O(\vec{\theta}, \vec{\nu})$$

depend usually on sub-set of $\vec{\theta}$ and $\vec{\nu}$

2) experimental data for each observable

$$\text{pdf}(O = o)$$

$\Rightarrow$ probability distribution of values o

"Global Fit" = combination of $b \to s + (\gamma, \ell^+\ell^-)$ observables

Parameters of interest

$$\vec{\theta} = (C_i)$$

Nuisance parameters

$\vec{\nu}$

1) process-specific
   - FF's, decay const's,
   - LCDA pmr's,
   - sub-leading Λ/m_b,
   - renorm. scales: $\mu_{b,0}$

2) general
   - quark masses, CKM, ...

Observables

1) observables

$$O(\vec{\theta}, \vec{\nu})$$

depend usually on sub-set of $\vec{\theta}$ and $\vec{\nu}$

2) experimental data for each observable

$$\text{pdf}(O = o)$$

$\Rightarrow$ probability distribution of values o

Fit strategies: 1) Put theory uncertainties in likelihood:

- sample $\vec{\theta}$-space (grid, Markov Chain, importance sampling...)

$$\chi^2 = \sum \frac{(O_{\rm ex} - O_{\rm th})^2}{\sigma_{\rm ex}^2 + \sigma_{\rm th}^2}$$

- theory uncertainties of O_i at each $(\vec{\theta})_i$: vary $\vec{\nu}$ within some ranges $\Rightarrow \sigma_{\rm th}(O[(\vec{\theta})_i])$
- use Frequentist or Bayesian method $\Rightarrow$ 68 & 95 % (CL or probability) regions of $\vec{\theta}$

“Global Fit” = combination of $b \to s + (\gamma, \ell^+\ell^-)$ observables

Parameters of interest

$$\vec{\theta} = (C_i)$$

Nuisance parameters

$\vec{\nu}$

1) process-specific

FF’s, decay const’s,
LCDA pmr’s,
sub-leading Λ/m_b,
renorm. scales: $\mu_{b,0}$

2) general

quark masses, CKM, . . .

Observables

1) observables

$$O(\vec{\theta}, \vec{\nu})$$

depend usually on sub-set of $\vec{\theta}$ and $\vec{\nu}$

2) experimental data for each observable

$$\text{pdf}(O = o)$$

$\Rightarrow$ probability distribution of values o

Fit strategies: 2) Fit also nuisance parameters:

- sample $(\vec{\theta} \times \vec{\nu})$-space (grid, Markov Chain, importance sampling...)
- accounts for theory uncertainties by fitting also $(\vec{\nu})_i$
- use Frequentist or Bayesian method $\Rightarrow$ 68 & 95 % (CL or probability) regions of $\vec{\theta}$ and $\vec{\nu}$

SM basis + real $C_{7,9,10}(4.2\,\mathrm{GeV})$

2D marginalised posterior

[Beaujean/CB/van Dyk/Wacker arXiv:1205.1838]

$\rightarrow$ individual constraints at 95 % CR from

$B \to K^* \gamma$ and

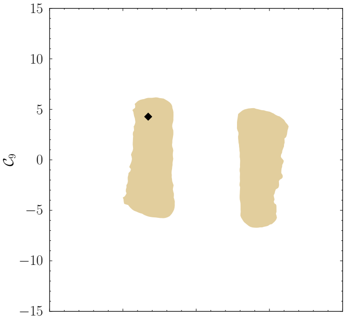
SM basis + real $\mathcal{C}_{7,9,10}(4.2\,\text{GeV})$

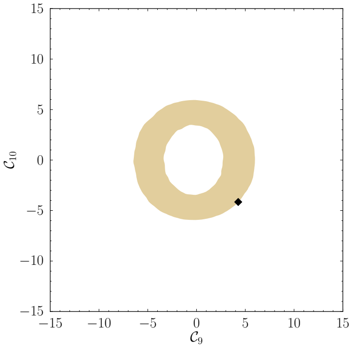
2D marginalised posterior

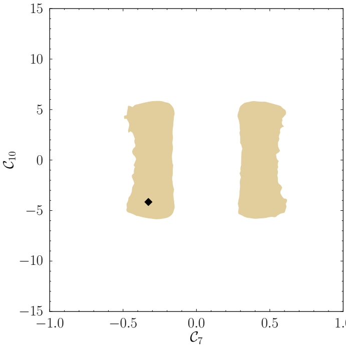
[Beaujean/CB/van Dyk/Wacker arXiv:1205.1838]

→ individual constraints at 95 % CR from

$B \to K^*\gamma$ and lo+hi-q^2 $B \to K\ell\bar{\ell}$







SM basis + real $C_{7,9,10}(4.2\,\text{GeV})$

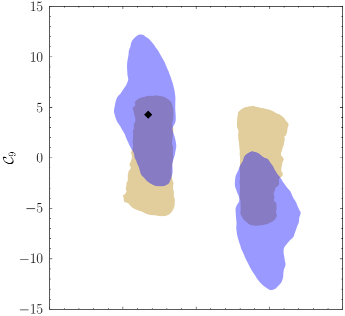
2D marginalised posterior

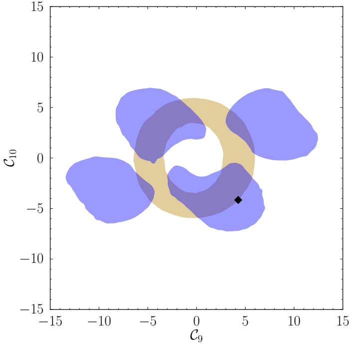
[Beaujean/CB/van Dyk/Wacker arXiv:1205.1838]

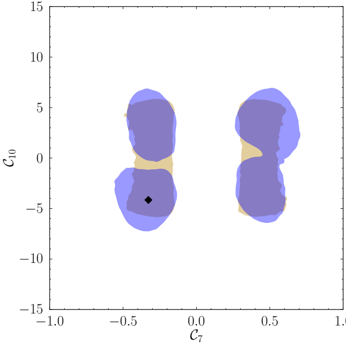
→ individual constraints at 95 % CR from

$B \to K^*\gamma$ and lo+hi-q^2 $B \to K\ell\bar{\ell}$

lo-q^2 $B \to K^*\ell\bar{\ell}$







SM basis + real $C_{7,9,10}(4.2\,\mathrm{GeV})$

2D marginalised posterior

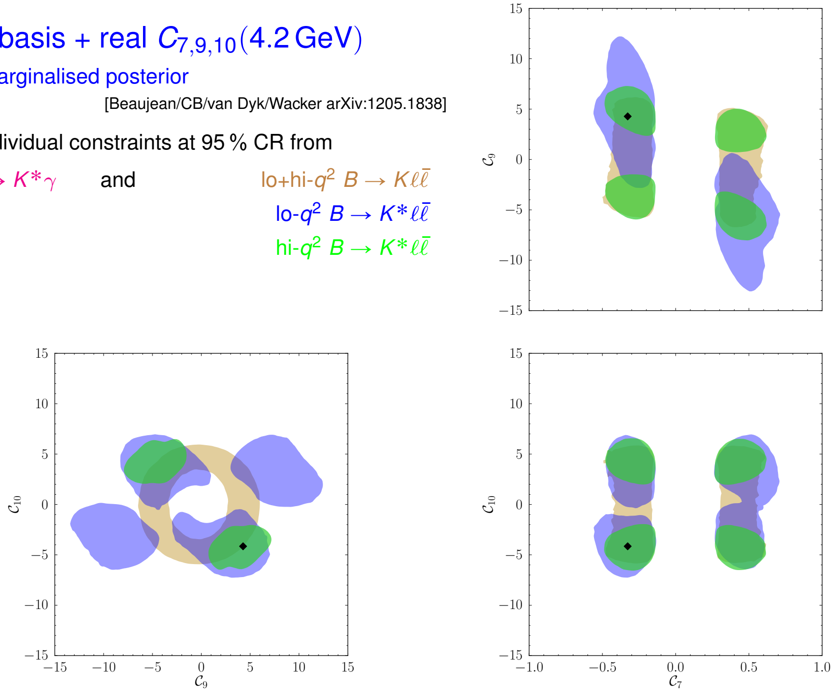
[Beaujean/CB/van Dyk/Wacker arXiv:1205.1838]

→ individual constraints at 95 % CR from

$B \to K^*\gamma$ and lo+hi-q^2 $B \to K\ell\bar{\ell}$

lo-q^2 $B \to K^*\ell\bar{\ell}$

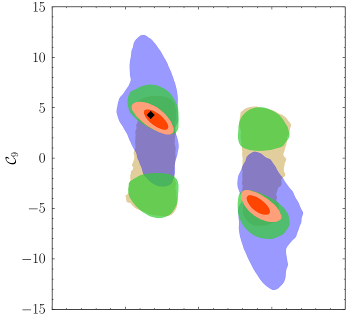
hi-q^2 $B \to K^*\ell\bar{\ell}$



SM basis + real $C_{7,9,10}(4.2\,\text{GeV})$

2D marginalised posterior

[Beaujean/CB/van Dyk/Wacker arXiv:1205.1838]



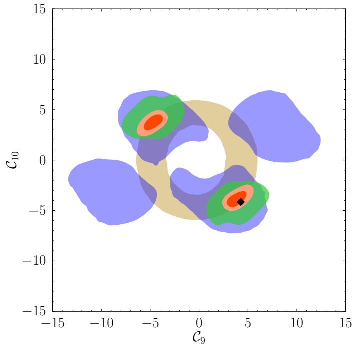
→ individual constraints at 95 % CR from

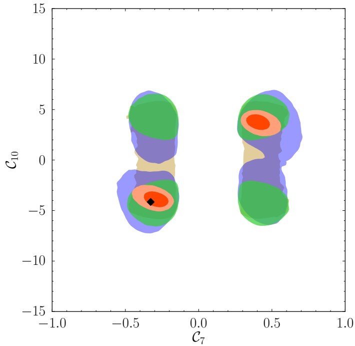
$B \to K^*\gamma$ and lo+hi-q^2 $B \to K\ell\bar{\ell}$

lo-q^2 $B \to K^*\ell\bar{\ell}$

hi-q^2 $B \to K^*\ell\bar{\ell}$

all constraints ($+B_s \to \mu\bar{\mu}$): 68 % (95 %) CR





SM basis + real $C_{7,9,10}(4.2\,\text{GeV})$

2D marginalised posterior

[Beaujean/CB/van Dyk/Wacker arXiv:1205.1838]

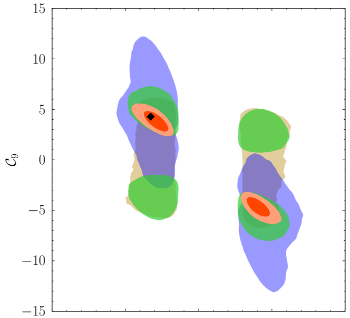
→ individual constraints at 95 % CR from

$B \to K^*\gamma$ and lo+hi-q^2 $B \to K\ell\bar{\ell}$

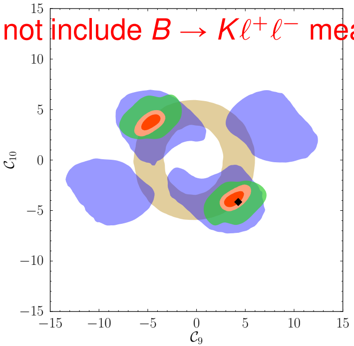
lo-q^2 $B \to K^*\ell\bar{\ell}$

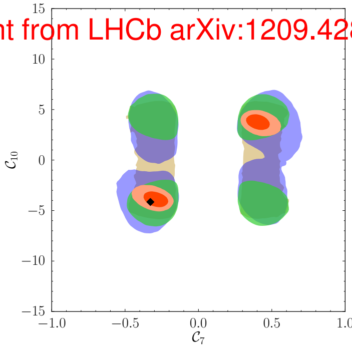
hi-q^2 $B \to K^*\ell\bar{\ell}$

all constraints ($+B_s \to \mu\bar{\mu}$): 68 % (95 %) CR



Did not include $B \to K\ell^+\ell^-$ measurement from LHCb arXiv:1209.4284

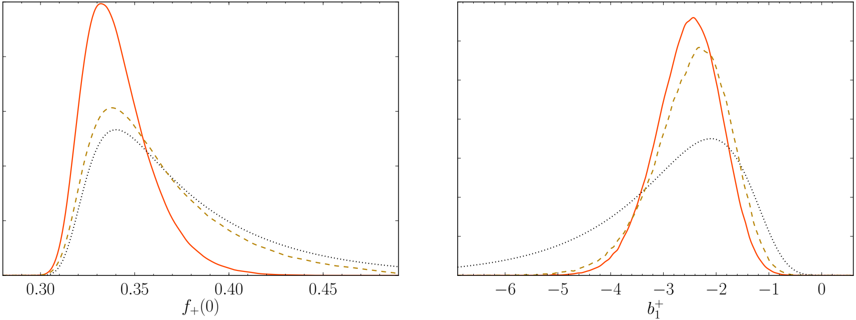




Nuisance parameter – example $B \to K$ form factor $f_+(q^2)$

$$f_+(q^2) = \frac{f_+(0)}{1 - q^2/M^2_{\mathrm{res},+}} \left[1 + b_1^+ \left(z(q^2) - z(0) + \frac{1}{2}\left[z(q^2)^2 - z(0)^2\right]\right)\right],$$

$$z(s) = \frac{\sqrt{\tau_+ - s} - \sqrt{\tau_+ - \tau_0}}{\sqrt{\tau_+ - s} - \sqrt{\tau_+ - \tau_0}}, \qquad \tau_0 = \sqrt{\tau_+}\left(\sqrt{\tau_+} - \sqrt{\tau_+ - \tau_-}\right), \qquad \tau_\pm = (M_B \pm M_K)^2$$



⇒ Prior [dotted] from LCSR calculation Khodjamirian/Mannel/Pivovarov/Wang arXiv:1006.4945

⇒ Posterior of $f_+(0)$ [left] and b_+^1 [right] using

1) $B \to K \ell^+ \ell^-$ data only [dashed] vs 2) all data [solid, red]

Altmannshofer/Paradisi/Straub
arXiv:1111.1257

and update in Altmannshofer/Straub
arXiv:1206.0273

$\Rightarrow$ based on MCMC + Bayesian inference

$\Rightarrow$ included data from

- $B \to X_s\,\gamma$: Br, A_{CP},
  $B \to K^*\gamma$: S
- $B \to X_s\,\ell\bar{\ell}$: Br,
  $B \to K\,\ell\bar{\ell}$: Br,
  $B \to K^*\ell\bar{\ell}$: Br, A_{FB}, F_L, S_3, A_{im},
  $B_s \to \mu\bar{\mu}$: Br

Altmannshofer/Paradisi/Straub
arXiv:1111.1257

and update in Altmannshofer/Straub
arXiv:1206.0273

$\Rightarrow$ based on MCMC + Bayesian inference

$\Rightarrow$ included data from

- $B \to X_s \gamma$: Br, $A_{\rm CP}$,
  $B \to K^* \gamma$: S
- $B \to X_s \ell\bar{\ell}$: Br,
  $B \to K \ell\bar{\ell}$: Br,
  $B \to K^* \ell\bar{\ell}$: Br, $A_{\rm FB}$, F_L, S_3, A_{im},
  $B_s \to \mu\bar{\mu}$: Br

$\Rightarrow$ model-indep. NP (real or complex)

- $C_{7,7',9,9',10,10'}$ (in varying stages)
- Z-penguin + $C_{7,7'}$
  $\Rightarrow$ relates $b \to s\,\ell\bar{\ell}$ and $b \to s\,\nu\bar{\nu}$
- $(C_S - C_{S'})$, $(C_P - C_{P'})$

Altmannshofer/Paradisi/Straub
arXiv:1111.1257

and update in Altmannshofer/Straub
arXiv:1206.0273

here in 2 parameter scenarios
from arXiv:1206.0273 $\Rightarrow$

$\Rightarrow$ individual constraints at 95 %

$S[B \to K^* \gamma]$

$Br[B \to X_s \gamma]$, $A_{CP}[B \to X_s \gamma]$

$Br[B \to X_s \ell^+ \ell^-]$

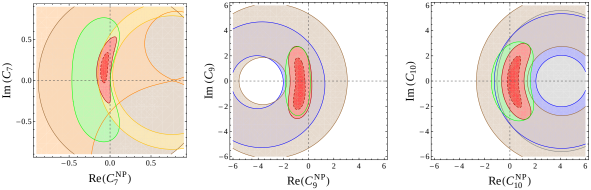
$B \to K \ell^+ \ell^-$

$B \to K^* \ell^+ \ell^-$

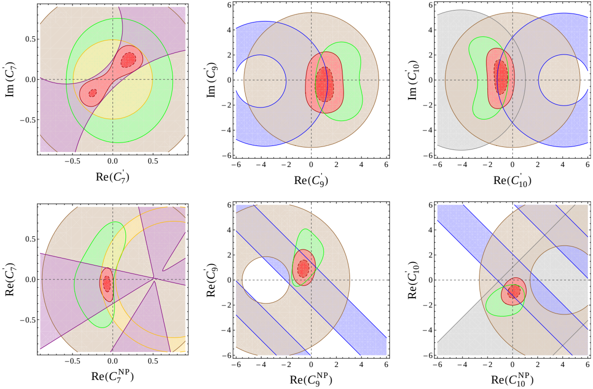
$B_s \to \mu^+ \mu^-$

comb. constraints: 68 % (95 %)

SM operators:



chirality-flipped operators:



Altmannshofer/Paradisi/Straub
arXiv:1111.1257

and update in Altmannshofer/Straub
arXiv:1206.0273

$\Rightarrow$ predictions of unmeasured observables

- still large T-odd CP-asymmetries

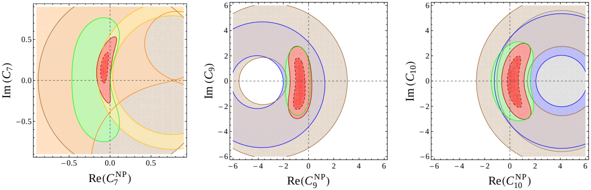
  at low-q^2:

  $$|\langle A_7 \rangle_{[1,6]}| < 35\,\%$$
  $$|\langle A_8 \rangle_{[1,6]}| < 21\,\%$$
  $$|\langle A_9 \rangle_{[1,6]}| < 13\,\%$$

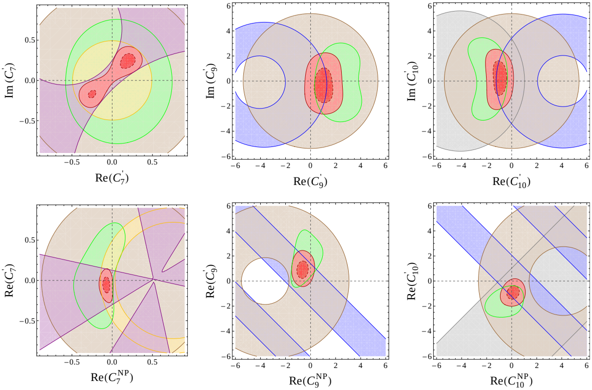
  at high-q^2:

  $$|\langle A_8 \rangle_{[14,16]}| < 12\,\%$$
  $$|\langle A_9 \rangle_{[14,16]}| < 20\,\%$$

SM operators:



chirality-flipped operators:



Altmannshofer/Paradisi/Straub arXiv:1111.1257

and update in Altmannshofer/Straub arXiv:1206.0273

$\Rightarrow$ predictions of unmeasured observables

- still large T-odd CP-asymmetries

  at low-q^2:

  $$|\langle A_7 \rangle_{[1,6]}| < 35\,\%$$
  $$|\langle A_8 \rangle_{[1,6]}| < 21\,\%$$
  $$|\langle A_9 \rangle_{[1,6]}| < 13\,\%$$

  at high-q^2:

  $$|\langle A_8 \rangle_{[14,16]}| < 12\,\%$$
  $$|\langle A_9 \rangle_{[14,16]}| < 20\,\%$$

Lower bounds (at 95% C.L.) on the NP scale Λ of dim-6 op's, assuming tree-FCNC $c_i = (+1,\, -1,\, +i,\, -i)$ & single operator

$$H_{\text{eff}} = \frac{c_i}{\Lambda^2} \mathcal{O}_i$$

Operator		Λ [TeV] for $\lvert c_i \rvert = 1$			
		$+$	$-$	$+i$	$-i$
$\mathcal{O}_7 =$	$\frac{m_b}{e}(\bar{s}\sigma_{\mu\nu} P_R b) F^{\mu\nu}$	69	270	43	38
$\mathcal{O}'_7 =$	$\frac{m_b}{e}(\bar{s}\sigma_{\mu\nu} P_L b) F^{\mu\nu}$	46	70	78	47
$\mathcal{O}_9 =$	$(\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)$	29	64	21	22
$\mathcal{O}'_9 =$	$(\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \ell)$	51	22	21	23
$\mathcal{O}_{10} =$	$(\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$	43	33	23	23
$\mathcal{O}'_{10} =$	$(\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$	25	89	24	23
$\mathcal{O}^{(\prime)}_S =$	$\frac{m_b}{m_{B_s}}(\bar{s} P_{R(L)} b)(\bar{\ell}\ell)$	93	93	98	98
$\mathcal{O}_P =$	$\frac{m_b}{m_{B_s}}(\bar{s} P_R b)(\bar{\ell}\gamma_5 \ell)$	173	58	93	93
$\mathcal{O}'_P =$	$\frac{m_b}{m_{B_s}}(\bar{s} P_L b)(\bar{\ell}\gamma_5 \ell)$	58	173	93	93

Relation $B_s \to \mu^+\mu^-$ and $B \to K\,\ell^+\ell^-$ interesting because ...

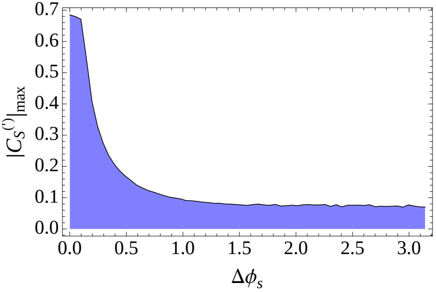
$\Rightarrow$ complementary dependence of

$$B_s \to \mu^+\mu^- \to (C_i - C_i') \qquad \text{for } i = 10,\ S,\ P$$

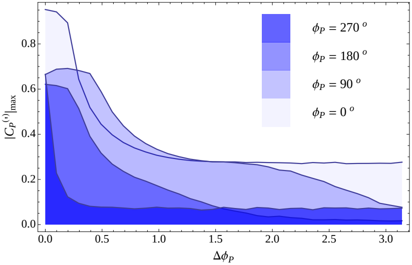
$$B \to K\,\ell^+\ell^- \to (C_i + C_i') \qquad \text{for } i = 7,\ 9,\ 10,\ S,\ P$$

$\Rightarrow$ to constrain scalar and pseudo-scalar operators

Only complex $C_{S,S'}$ with relative phase $\Delta\phi_S$



Only complex $C_{P,P'}$ with relative phase $\Delta\phi_P$ and phase ϕ_P of C_P



[Becirevic/Kosnik/Mescia/Schneider arXiv:1205.5811]

Relation $B_s \to \mu^+\mu^-$ and $B \to K\,\ell^+\ell^-$ interesting because ...

$\Rightarrow$ complementary dependence of

$B_s \to \mu^+\mu^- \to (C_i - C_i')$ for $i = 10,\ S,\ P$

$B \to K\,\ell^+\ell^- \to (C_i + C_i')$ for $i = 7,\ 9,\ 10,\ S,\ P$

$\Rightarrow$ to constrain scalar and pseudo-scalar operators

$\Rightarrow$ $B \to K\,\ell^+\ell^-$ ($A_{\rm FB}$, F_H) constrain also T, $T5$

LHCb measurement of F_H arXiv:1209.4284

@ high-q^2 : $q^2 \in [14.2,\ 16.0],\ [16.0,\ 18.0],\ [18.0,\ 22.0]$ GeV^2 implies bound

$$|C_T|^2 + |C_{T5}|^2 \lesssim 0.5$$

assuming single operator dominance

$$F_H \sim \frac{m_\ell^2/q^2 \times \text{SM} + (|C_T|^2 + |C_{T5}|^2)}{\text{SM} \qquad + (|C_T|^2 + |C_{T5}|^2)}$$

!!! form factor f_+ cancels

[CB/Hiller/van Dyk arXiv:1212.2321]

Summary

Implications Summary

- measurements (before mid-2012) of Belle, CDF, Babar, LHCb, CMS, ATLAS on rare $B \to (K, K^*)\ell^+\ell^-$ and $B_s \to \mu^+\mu^-$ consistent with SM:

  $\Rightarrow$ two solutions for $C_{7,9,10}$: SM-like sign and sign-flipped

  $\to B \to X_s\gamma$ or other obs. sensitive to eff. part of $C_{7,9}^{\text{eff}}$ might resolve this

  $\Rightarrow Br(B \to K\mu^+\mu^-)$ @ low-q^2 lower than SM

- beyond SM:

  $\Rightarrow B_s \to \mu^+\mu^-$ puts stronger constraints on $C^{(\prime)}_{S,P,10}$

  $\Rightarrow B \to K\mu^+\mu^-$ constrains $(C_{9,10,S,P} + C_{9',10',S',P'})$ and $C_{T,T5}$

!!! Currently measured only obs's with rather large theory uncertainties

EOS = Flavour tool @ TU Dortmund by Danny van Dyk et al.

Download @ http://project.het.physik.tu-dortmund.de/eos/

Outlook

- new $b \to s + (\gamma, \ell^+\ell^-)$ data from LHCb, CMS, ATLAS

  $\Rightarrow$ LHCb additional 2.2 fb^{-1} to analyze by the end of 2012

  $\Rightarrow$ CMS and ATLAS add. $\gtrsim$ 15 fb^{-1} in 2012 to search for $B_s \to \mu^+\mu^-$

  and from 2nd generation Flavor-factory Belle II $\gtrsim$ 2020

  However, high exp. statistics $\to$ need to account for S-wave $(K\pi)$-pairs in $B \to K^*\ell^+\ell^-$ [Becirevic/Tayduganov arXiv:1207.4004, Blake/Egede/Shires arXiv:1210.5279]

- first measurements of optimized observables

  in exclusive $B \to K^*(\to K\pi)\ell^+\ell^-$ @ low- and high-q^2

  $\Rightarrow$ combinations with small hadronic uncertainties

- first lattice results of form factors $B \to K$ and $B \to K^*$

  @ high-q^2 should become available

– Backup Slides –

Remark on $Br[B_s \to \mu^+\mu^-]$

So far theorists neglected mixing of B_s $\Rightarrow$ predict Br at $t = 0$: $Br[B_s(t = 0) \to \bar{\mu}\mu]$

Remark on $Br[B_s \to \mu^+\mu^-]$

So far theorists neglected mixing of B_s $\Rightarrow$ predict Br at $t = 0$: $Br[B_s(t = 0) \to \bar{\mu}\mu]$

But with new measurements of $\Delta\Gamma_s$ (incl. sign) from LHCb and CDF, DØ

$\Rightarrow$ experiments actually measure time-integrated Br: [De Bruyn et al. arXiv:1204.1737]

$$Br[B_s \to \bar{\mu}\mu] \equiv \frac{1}{2}\int_0^\infty dt\, \Big(\Gamma[B_s(t) \to \bar{\mu}\mu] + \Gamma[\overline{B}_s(t) \to \bar{\mu}\mu]\Big)$$

$$= \frac{1 + y_s \cdot \mathcal{A}_{\Delta\Gamma}}{1 - y_s^2}\, Br[B_s(t = 0) \to \bar{\mu}\mu]$$

with (LHCb '11)

$$y_s = \frac{\Delta\Gamma_s}{2\,\Gamma_s} = 0.088 \pm 0.014$$

and

$\Rightarrow$ in SM $\quad \mathcal{A}_{\Delta\Gamma}|_{\mathrm{SM}} = +1$

$\Rightarrow$ beyond $\mathcal{A}_{\Delta\Gamma} \in [-1, +1]$ $\to$ depends on NP !!!

Remark on $Br[B_s \to \mu^+\mu^-]$

So far theorists neglected mixing of B_s $\Rightarrow$ predict Br at $t = 0$: $Br[B_s(t=0) \to \bar{\mu}\mu]$

But with new measurements of $\Delta\Gamma_s$ (incl. sign) from LHCb and CDF, DØ

$\Rightarrow$ experiments actually measure time-integrated Br: [De Bruyn et al. arXiv:1204.1737]

$$Br[B_s \to \bar{\mu}\mu] \equiv \frac{1}{2}\int_0^\infty dt\, \Big(\Gamma[B_s(t) \to \bar{\mu}\mu] + \Gamma[\overline{B}_s(t) \to \bar{\mu}\mu]\Big)$$

$$= \frac{1 + y_s \cdot \mathcal{A}_{\Delta\Gamma}}{1 - y_s^2}\, Br[B_s(t=0) \to \bar{\mu}\mu]$$

with (LHCb '11)

$$y_s = \frac{\Delta\Gamma_s}{2\,\Gamma_s} = 0.088 \pm 0.014$$

and

$\Rightarrow$ in SM $\quad \mathcal{A}_{\Delta\Gamma}|_{\rm SM} = +1$

$\Rightarrow$ beyond $\mathcal{A}_{\Delta\Gamma} \in [-1, +1]$ $\to$ depends on NP !!!

In SM for example

$$Br[B_s \to \bar{\mu}\mu]_{\rm SM} = (3.53 \pm 0.38) \times 10^{-9}$$

[Mahmoudi/Neshatpour/Orloff arXiv:1205.1845]

largest uncertainties from

$f_{B_s} = (234 \pm 10)$ MeV $\to 9\,\%$

$V_{ts} \to 5\,\%$

B_s lifetime $\to 2\,\%$

Remark on $Br[B_s \to \mu^+\mu^-]$

So far theorists neglected mixing of B_s $\Rightarrow$ predict Br at $t = 0$: $Br[B_s(t=0) \to \bar{\mu}\mu]$

But with new measurements of $\Delta\Gamma_s$ (incl. sign) from LHCb and CDF, DØ

$\Rightarrow$ experiments actually measure time-integrated Br: [De Bruyn et al. arXiv:1204.1737]

$$Br[B_s \to \bar{\mu}\mu] \equiv \frac{1}{2}\int_0^\infty dt \left(\Gamma[B_s(t) \to \bar{\mu}\mu] + \Gamma[\overline{B}_s(t) \to \bar{\mu}\mu]\right)$$

$$= \frac{1 + y_s \cdot \mathcal{A}_{\Delta\Gamma}}{1 - y_s^2} Br[B_s(t=0) \to \bar{\mu}\mu]$$

with (LHCb '11)

$$y_s = \frac{\Delta\Gamma_s}{2\,\Gamma_s} = 0.088 \pm 0.014$$

and

$\Rightarrow$ in SM $\quad \mathcal{A}_{\Delta\Gamma}|_{\mathrm{SM}} = +1$

$\Rightarrow$ beyond $\mathcal{A}_{\Delta\Gamma} \in [-1, +1]$ $\to$ depends on NP !!!

... or using precise ΔM_s measurement to substitute f_{B_s} (and assuming SM) [Buras hep-ph/0303060]

$$Br[B_s \to \bar{\mu}\mu]_{\mathrm{SM}} = \frac{(3.1 \pm 0.2) \times 10^{-9}}{0.91 \pm 0.01} = (3.4 \pm 0.2) \times 10^{-9}$$

[Buras/Girrbach arXiv:1204.5064]

Goodness of fit & Bayes factor

[Beaujean/CB/van Dyk/Wacker arXiv:1205.1838]

sgn(C_7, C_9, C_{10})	best-fit-point	log(MAP)	goodness-of-fit				log(Z)
			T_{like}	p_{like}	T_{pull}	p_{pull}	
$(-, +, -)$	$(-0.295, 3.73, -4.14)$	424.31	402.40	59%	48.8	74%	385.1
$(+, -, +)$	$(0.418, -4.64, 3.99)$	424.20	402.32	58%	48.9	74%	385.0
$(-, -, +)$	$(-0.392, -3.09, 3.19)$	403.72	387.70	0.8%	76.8	3%	363.8
$(+, +, -)$	$(0.557, 2.25, -3.24)$	399.70	384.66	0.2%	82.9	1%	360.1
SM: $(-, +, -)$	$(-0.327, 4.28, -4.15)$	430.56†	402.30	69%	49.0	82%	392.4

MAP = maximum a posteriori

Z = local evidence $= \int d\vec{\theta}\, d\vec{\nu}\, P(D|\theta, \nu) \cdot P(\theta, \nu) =$ "likelihood $\times$ prior"

$\Rightarrow$ 2 methods to derive p-values from 2 statistics T_{like} and T_{pull}:

indicate good fit: $p \sim (60 - 75)\%$

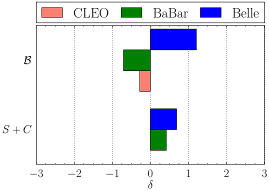
$\Rightarrow$ model comparison: SM = fixed values of Wilson coefficients $\Leftrightarrow$ SM-like solution

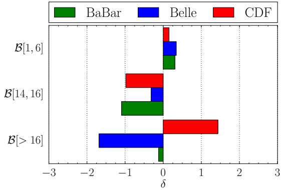
Bayes factor: $B = \exp(392.4 - 385.1) \approx 1500$ in favor of the simpler model

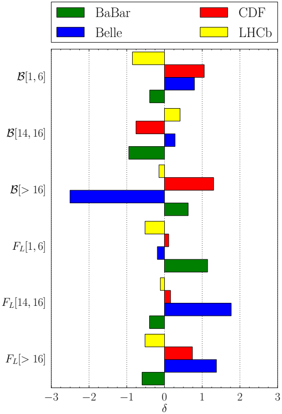
Pull values of experimental observables

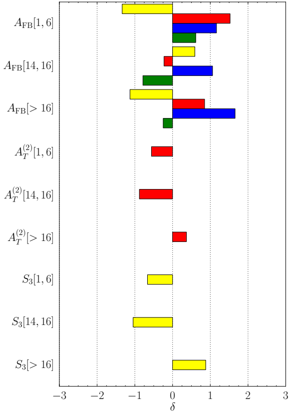
[Beaujean/CB/van Dyk/Wacker arXiv:1205.1838]

22 observables with 59 measurements: $B \to K^*\gamma$, $B \to K\,\ell^+\ell^-$, $B \to K^*\ell^+\ell^-$









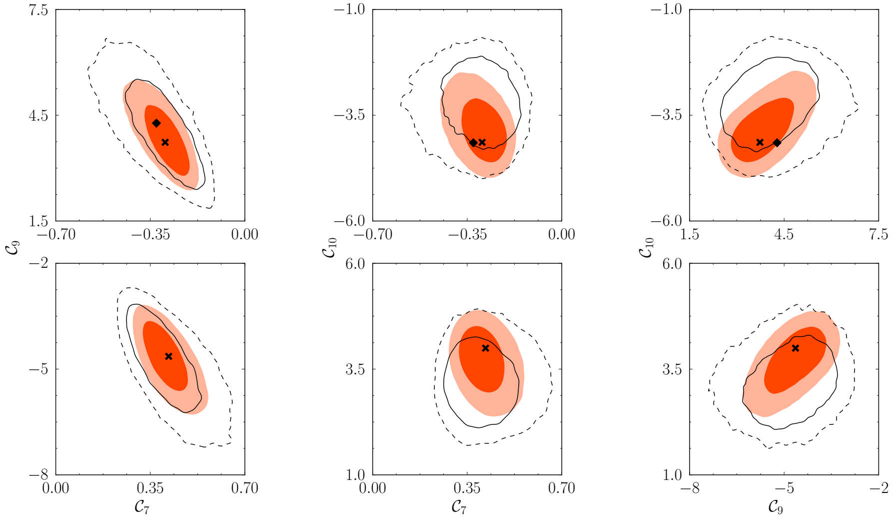
pull definition

$$\delta = \frac{x_{pred}(\vec{\theta}, \vec{\nu}) - x}{\sigma}$$

$x_{pred}(\vec{\theta}, \vec{\nu})$	theory prediction at best fit point
x	central value of experimental distribution
σ	experimental uncertainty

Prior dependence

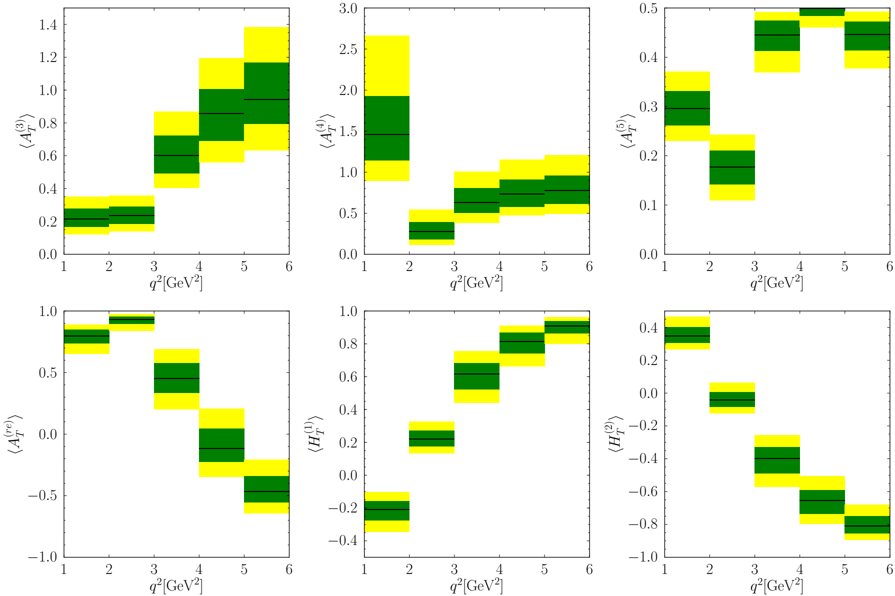
SM = (◆), best fit point = (×)



95 % (dashed) and 68 % (solid) credibility regions using 3× larger prior ranges

⇒ fit still converges

Prediction of yet unmeasured optimized observables @ low-q^2



⇒ Measurements outside these predictions would put simple scenario $C_{7,9,10}$ in trouble

High-q^2: OPE + HQET

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

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

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

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

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

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

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