Implications of the experimental results on rare $b \to s + (\gamma,\, \ell^+\ell^-)$ decays

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7th CKM-Workshop – Cincinnati – 2012

$\Delta B = 1$ 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_{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

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

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

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

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

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

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

$B_s \to \gamma\gamma$

– Br ($A_{\rm CP}$)

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

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

$i = 7, 7'$

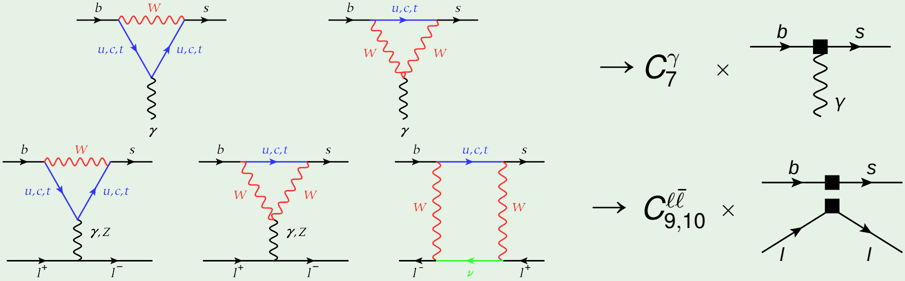
$i = 7^{(\prime)}, 9^{(\prime)}, 10^{(\prime)}, S^{(\prime)}, P^{(\prime)}, T(5), \ldots$

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

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

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



$$\mathcal{O}_7^\gamma = \frac{e}{(4\pi)^2} m_b [\bar s\, \sigma^{\mu\nu} P_R\, b] F_{\mu\nu}, \qquad \mathcal{O}_{9,10}^{\ell\bar\ell} = \frac{\alpha_e}{4\pi} [\bar s\, \gamma^\mu P_L\, b][\bar\ell\, \gamma_\mu (1,\, \gamma_5)\, \ell]$$

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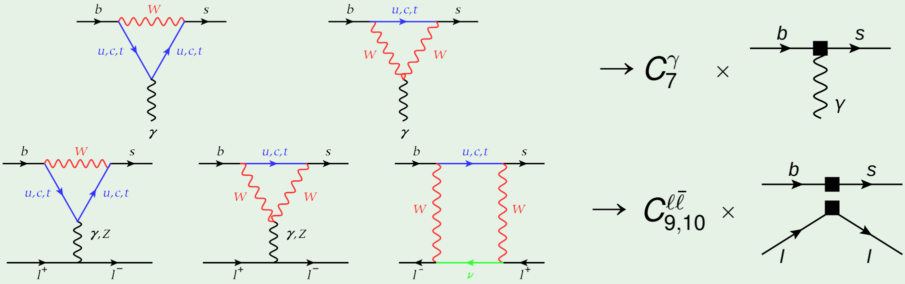

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and

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

⇒ 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

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S + P = scalar + pseudoscalar

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T + T5 = tensor

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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

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Extension of EFT beyond the SM . . .

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

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

- ⇒ ΔC_i . . . NP contributions to SM C_i
- ⇒ $\sum_{\text{NP}} C_j \mathcal{O}_j$ . . . NP operators (e.g. $C'_{7,9,10}$, $C^{(\prime)}_{S,P}$, . . .)
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2) RG-running to lower scale $\mu_b \sim m_b$ (potentially tower of EFT's)

C_i are correlated, depend on fundamental parameters

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Experimental results

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

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

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

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 6.8 fb^{-1}	LHCb 2011/12 1 fb^{-1}
$B^0 \to K^{*0}\,\ell\bar{\ell}$	$137 \pm 44^\dagger$	$247 \pm 54^\dagger$	164 ± 15	900 ± 34
$B^+ \to K^{*+}\,\ell\bar{\ell}$			20 ± 6	76 ± 16
$B^+ \to K^+\,\ell\bar{\ell}$	$153 \pm 41^\dagger$	$162 \pm 38^\dagger$	234 ± 19	1232 ± 40
$B^0 \to K_S^0\,\ell\bar{\ell}$			28 ± 9	60 ± 19
$B_s \to \phi\,\ell\bar{\ell}$			49 ± 7	77 ± 10
$\Lambda_b \to \Lambda\,\ell\bar{\ell}$			24 ± 5	
$B^+ \to \pi^+\,\ell\bar{\ell}$		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
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Outlook / Prospects

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CDF	recorded about 9.6 fb^{-1} $\to$ final analysis presented at ICHEP 2012
LHCb	about 3.2 fb^{-1} by end of 2012 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 / SuperB	expects about (10-15) K events $B \to K^* \ell\bar{\ell}$ ($\gtrsim$ 2020) [A.J.Bevan arXiv:1110.3901]

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More details on data

BaBar	Jack RITCHIE	$B \to K^* \ell^+\ell^-$	this session
CDF	Satyajit BEHARI	$B \to K^* \ell^+\ell^-$	this session
Belle	Cholong LIM	$b \to s\gamma$	today afternoon session
BaBar	Jack RITCHIE	$b \to s\gamma$	today afternoon session
LHCb	Flavio ARCHILLI	$B_q \to \ell^+\ell^-$	tomorrow session
ATLAS/CMS	Bakul GAUR	$B_q \to \ell^+\ell^-$	tomorrow session
CDF	Kevin PITTS	$B_q \to \ell^+\ell^-$	tomorrow session

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

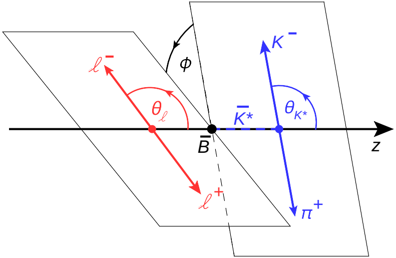
4-body decay with on-shell $\overline{K}^*$ (vector)

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



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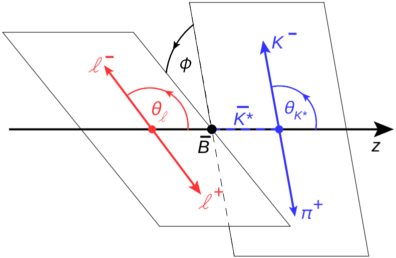

$J_i(q^2)$ = "Angular Observables"

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$$+ (J_{6s}\sin^2\theta_K + J_{6c}\cos^2\theta_K)\cos\theta_\ell + J_7 \sin 2\theta_K \sin\theta_\ell \sin\phi$$
$$+ J_8 \sin 2\theta_K \sin 2\theta_\ell \sin\phi + J_9 \sin^2\theta_K \sin^2\theta_\ell \sin 2\phi$$

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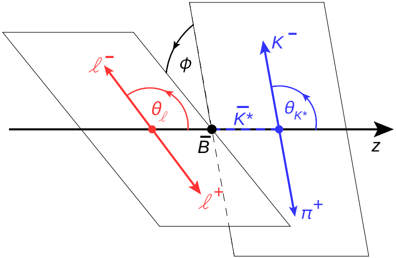

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$\Rightarrow$ "$2 \times (12 + 12) = 48$" if measured separately: A) decay + CP-conj and B) for $\ell = e, \mu$

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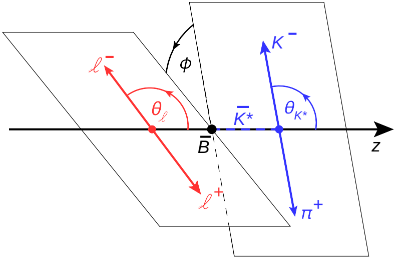
4) ϕ $\angle(\vec{p}_{\bar{K}} \times \vec{p}_\pi, \vec{p}_{\bar{\ell}} \times \vec{p}_\ell)$ in B-RF



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 $\bar{B} \to \bar{K}^* [\to \bar{K}\pi] + \ell^+\ell^-$

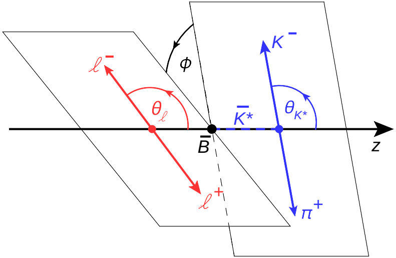
4-body decay with on-shell $\bar{K}^*$ (vector)

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

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

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

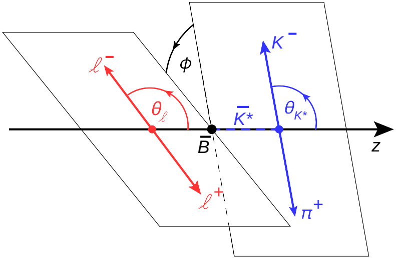
4-body decay with on-shell $\overline{K}^*$ (vector)

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

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

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

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



Attention!!! different θ_ℓ in $\overline{B} \to \overline{K}^*$ and $B \to K^*$ decays used by Belle, CDF, BaBar:

$$\text{CP-even} : J_{1,2,3,4,5,6} \longrightarrow +\bar{J}_{1,2,3,4,5,6}[\delta_W \to -\delta_W]$$

$$\text{CP-odd} : J_{7,8,9} \longrightarrow -\bar{J}_{7,8,9}[\delta_W \to -\delta_W]$$

θ_ℓ between $\overline{B}$ (B) and ℓ^- (ℓ^+) in $\overline{B} \to \overline{K}^*$ ($B \to K^*$)

!!! Not possible in $\overline{B}_s, B_s \to \phi(\to K^+K^-)\,\ell^+\ell^-$ since not self-tagging

Currently, LHCb θ_ℓ as Belle, CDF, BaBar and ϕ differently for $\overline{B} \to \overline{K}^*$ and $B \to K^*$

$\Rightarrow$ only CP-even J_i [LHCb-CONF-2012-008]

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_{FB}, F_L

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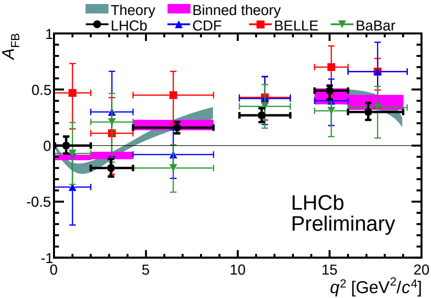
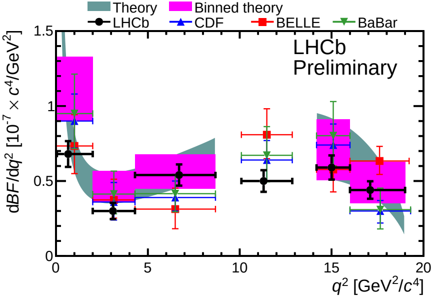
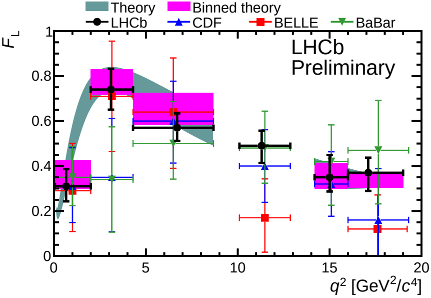
$\Rightarrow$ fitted F_L and A_{FB}

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

form factors Ball/Zwicky hep-ph/0412079







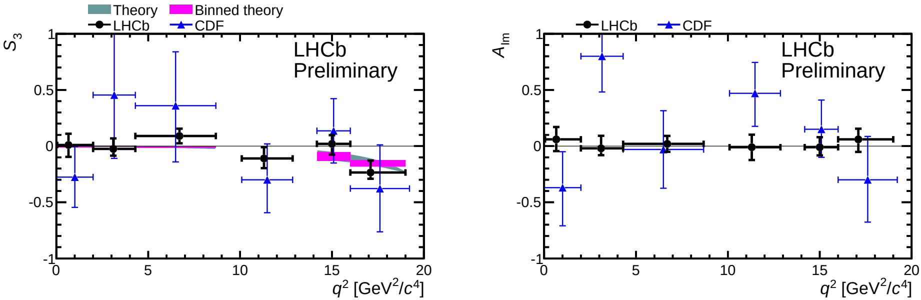
Data for $B \to K^* + \ell^+\ell^-$:

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

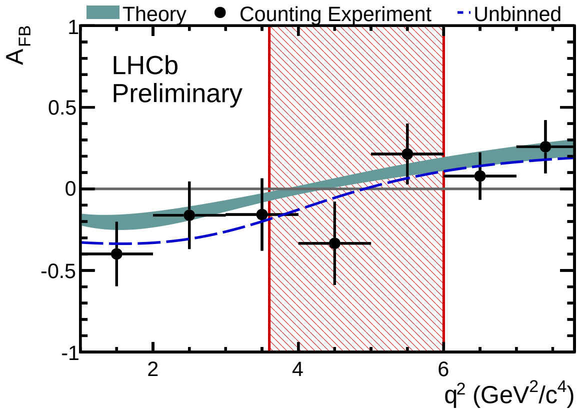
$$S_3 = \frac{J_3 + \overline{J}_3}{\Gamma + \bar{\Gamma}} = \frac{1}{2}(1 - F_L)\, A_T^{(2)}, \qquad A_{im} = A_9 = \frac{J_9 - \overline{J}_9}{\Gamma + \bar{\Gamma}}, \qquad S_9 = \frac{J_9 + \overline{J}_9}{\Gamma + \bar{\Gamma}},$$



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

Zero-crossing of A_{FB} in low-q^2 region: [LHCb Collaboration LHCb-CONF-2012-008]

finer q^2-binning than previously: bin-width $= 1$ GeV^2



Measurement:

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

"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

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

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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

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

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

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

CB/Hiller/van Dyk arXiv:1006.5013

Matias/Mescia/Ramon/Virto arXiv:1202.4266 + 1207.2753

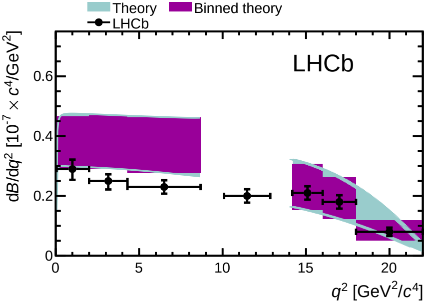
CB/Hiller/van Dyk in preparation, van Dyk PhD-thesis

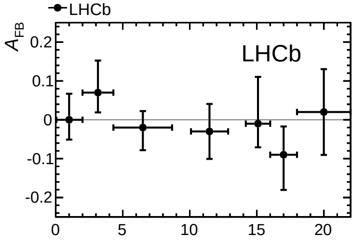
$B \to K + \ell^+\ell^-$: 3-body decay $\to$ 2 kinematic variables: q^2, θ_ℓ

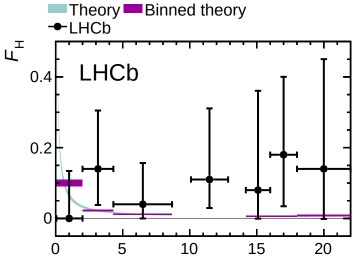
$$\frac{1}{(\mathrm{d}\Gamma/\mathrm{d}q^2)}\frac{\mathrm{d}^2\Gamma}{\mathrm{d}q^2\,\mathrm{d}\cos\theta_\ell} = \frac{3}{4}\left[1 - F_H\right]\sin^2\theta_\ell + \frac{1}{2}F_H + A_{\rm FB}\cos\theta_\ell$$

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

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







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

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

Remark on form factors (FF)

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

⇒ @ 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, $\ldots$

⇒ in progress → see talk by Ran ZHOU this session

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

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

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time-integrated accounting for B_s-mixing

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

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

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

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

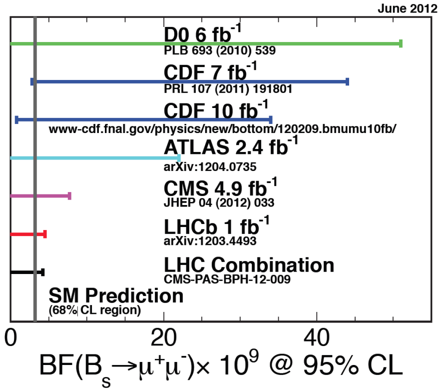
  $$\mathcal{O}(10^{-6}) \to \mathcal{O}(10^{-8})$$

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

  $\Rightarrow$ LHC Combination @ 95% CL

  $=$ LHCb + ATLAS + CMS

$$Br[B_s \to \mu^+\mu^-] < 4.2 \times 10^{-9}$$



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, ...

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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

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$\vec{\nu}$

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   - FF’s, decay const’s,
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Observables

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

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:

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

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

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

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   - 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 $C_{7,9,10}(4.2\,\text{GeV})$

2D marginalised posterior

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

$\rightarrow$ individual constraints at 95 % CR from

$B \rightarrow K^*\gamma$ and

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

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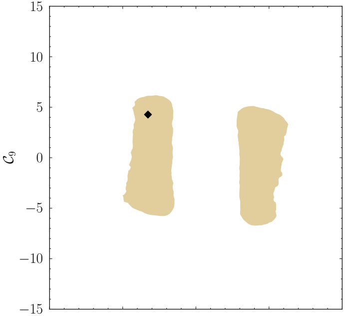
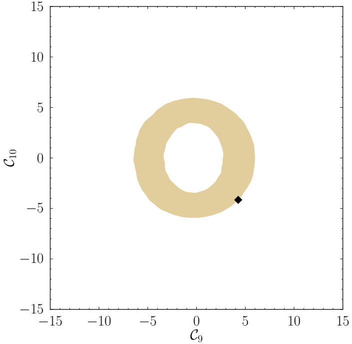
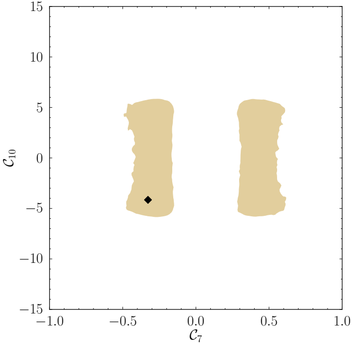






SM basis + real $C_{7,9,10}(4.2\,\text{GeV})$

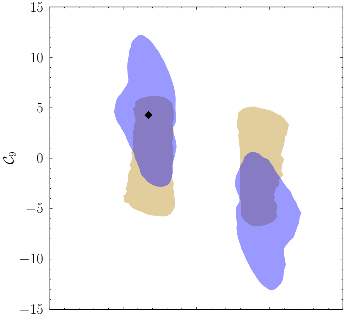
2D marginalised posterior

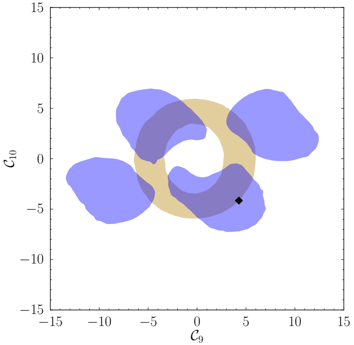
[Beaujean/CB/van Dyk/Wacker arXiv:1205.1838]

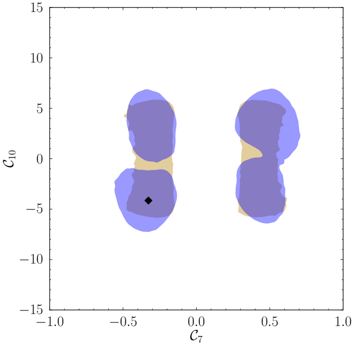
→ individual constraints at 95 % CR from

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

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







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

2D marginalised posterior

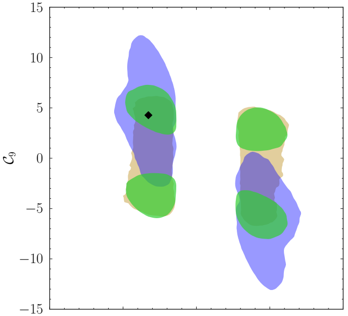
[Beaujean/CB/van Dyk/Wacker arXiv:1205.1838]

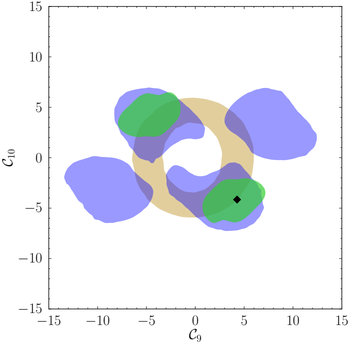
→ individual constraints at 95 % CR from

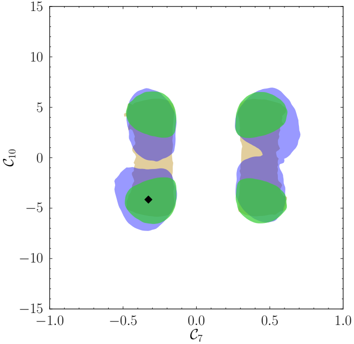
$B \to K^*\gamma$ and lo+hi-q^2 $B \to K\ell\bar{\ell}$

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

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







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

2D marginalised posterior

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

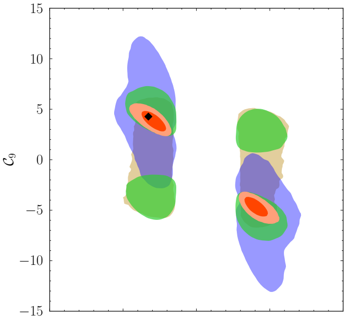
→ individual constraints at 95 % CR from

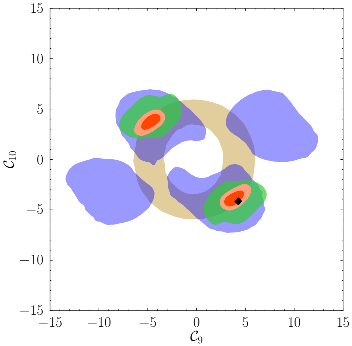
$B \to K^*\gamma$ and lo+hi-q^2 $B \to K\ell\bar{\ell}$

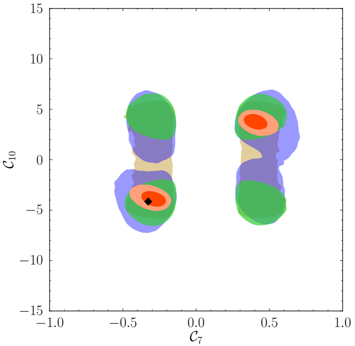
lo-q^2 $B \to K^*\ell\bar{\ell}$

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

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



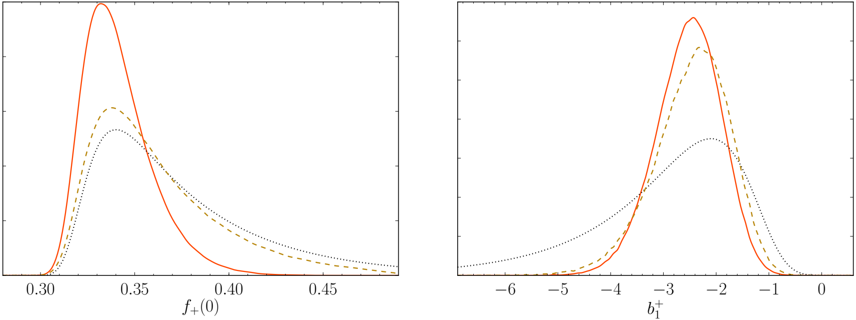




Nuisance parameter – example $B \to K$ form factor $f_+(q^2)$

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

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



⇒ 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, $A_{\rm CP}$,
  $B \to K^* \gamma$: 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

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  $B_s \to \mu\bar{\mu}$: 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 ⇒

⇒ individual constraints at 95 %

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

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

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

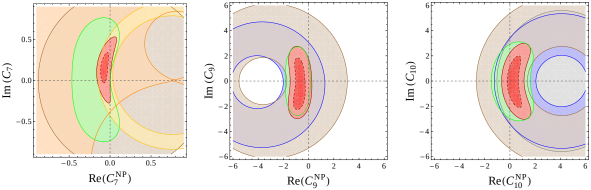
$B \to K \ell^+ \ell^-$

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

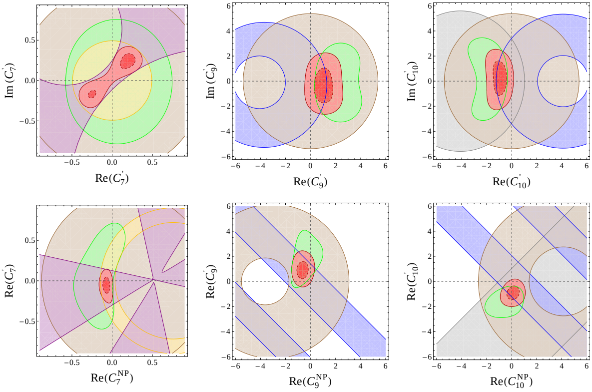
$B_s \to \mu^+ \mu^-$

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:

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

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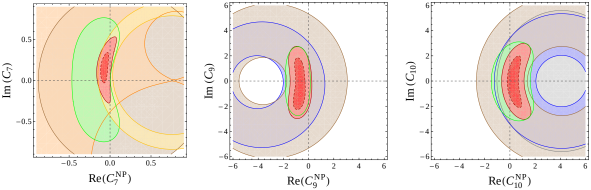

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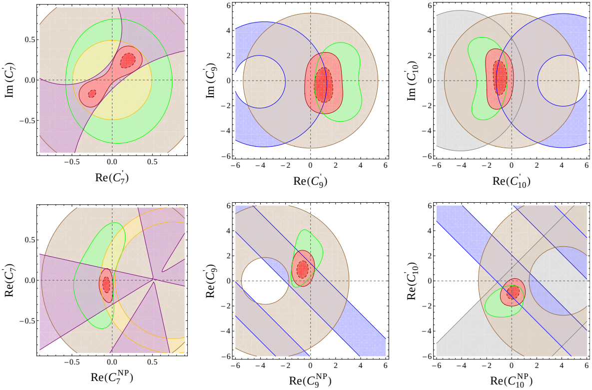

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Operator		Λ [TeV] for $|c_i| = 1$			
		$+$	$-$	$+i$	$-i$
$\mathcal{O}_7 =$	$\frac{m_b}{e}(\bar{s}\sigma_{\mu\nu}P_R b)F^{\mu\nu}$	69	270	43	38
$\mathcal{O}'_7 =$	$\frac{m_b}{e}(\bar{s}\sigma_{\mu\nu}P_L b)F^{\mu\nu}$	46	70	78	47
$\mathcal{O}_9 =$	$(\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu\ell)$	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
$\mathcal{O}_S^{(\prime)} =$	$\frac{m_b}{m_{B_s}}(\bar{s}P_{R(L)}b)(\bar{\ell}\ell)$	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

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

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

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

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

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

convert A_{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)

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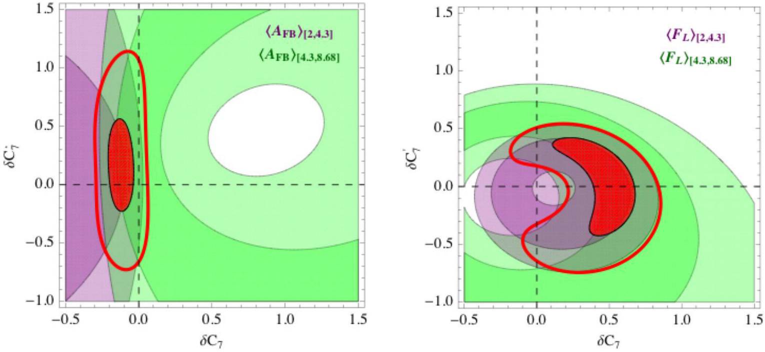
in $\delta C_7 - \delta C_{7'}$ plane $A_{\rm FB}$ and F_L



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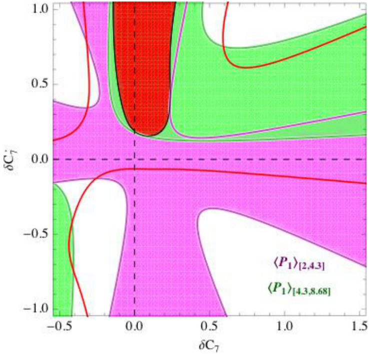
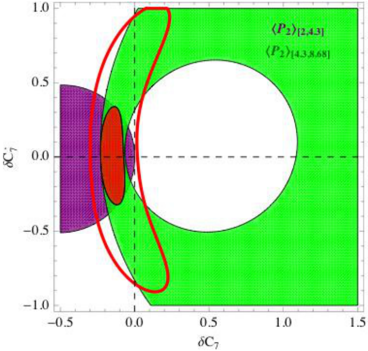




Relation $B_s \to \mu^+\mu^-$ and $B \to K\,\ell^+\ell^-$ interesting because ...

$\Rightarrow$ complementary dependence of

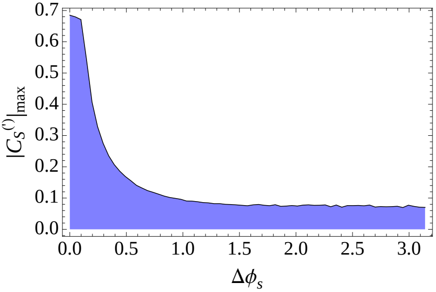
$B_s \to \mu^+\mu^- \to (C_i - C_i')$ for $i = 10,\ S,\ P$

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

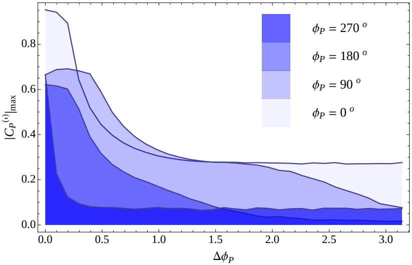
$\Rightarrow$ to constrain scalar and pseudo-scalar operators

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

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]

Further analysis based on new data

Model-independent

- Becirevic/Kou/Le Yaounac/Tayduganov arXiv:1206.1502
- Hurth/Mahmoudi arXiv:1207.0688
- Descotes-Genon/Matias/Ramon/Virto arXiv:1207.2753

Model-dependent

- Behring/Gross/Hiller/Schacht arXiv:1205.1500
- Mahmoudi/Neshatpour/Orloff arXiv:1205.1845
- Kosnik arXiv:1206.2970

Implications Summary

- latest results of Belle, CDF, Babar, LHCb, CMS and 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

  $\rightarrow$ $B \to X_s\gamma$ or other obs. sensitive to eff. part of $C_{7,9}^{\rm eff}$ 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 $C_{S,P}^{(\prime)}$

  $\Rightarrow$ $B_s \to \mu^+\mu^-$ and $B \to K\mu^+\mu^-$ constrain $(C_{9,10} \pm C'_{9,10})$

!!! 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-factories Belle II, SuperB $\gtrsim$ 2020

- 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 $t = 0$: $Br[B_s(t = 0) \to \bar{\mu}\mu]$

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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 !!!

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In SM for example

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

[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 $\to 2\,\%$

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... 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]

$\text{sgn}(C_7, C_9, C_{10})$	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: $(-, +, -)$	$(-0.327, 4.28, -4.15)$	$430.56^\dagger$	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: $p \sim (60 - 75)\%$

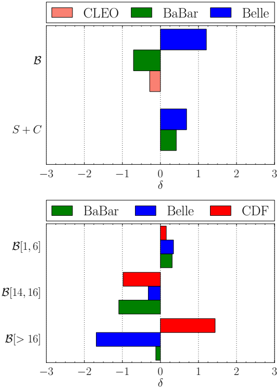
$\Rightarrow$ model comparison: SM = fixed values of Wilson coefficients $\Leftrightarrow$ SM-like solution

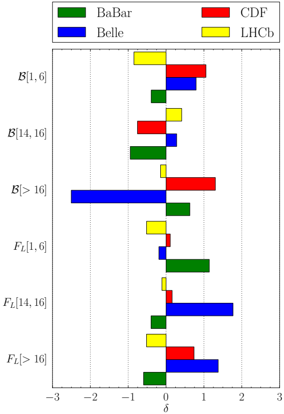
Bayes factor: $B = \exp(392.4 - 385.1) \approx 1500$ in favor of the simpler model

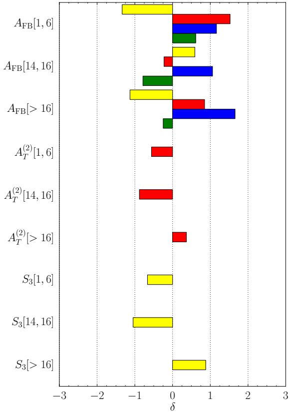
Pull values of experimental observables

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

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







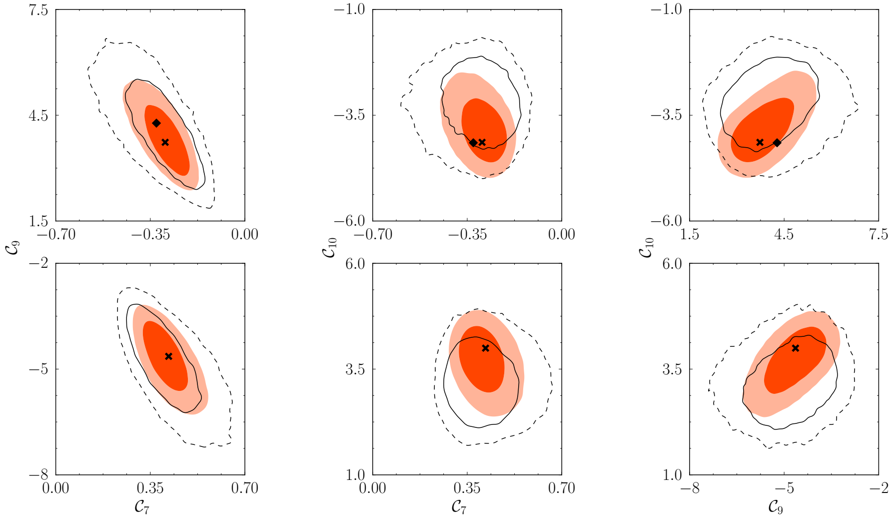
pull definition

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

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

Prior dependence

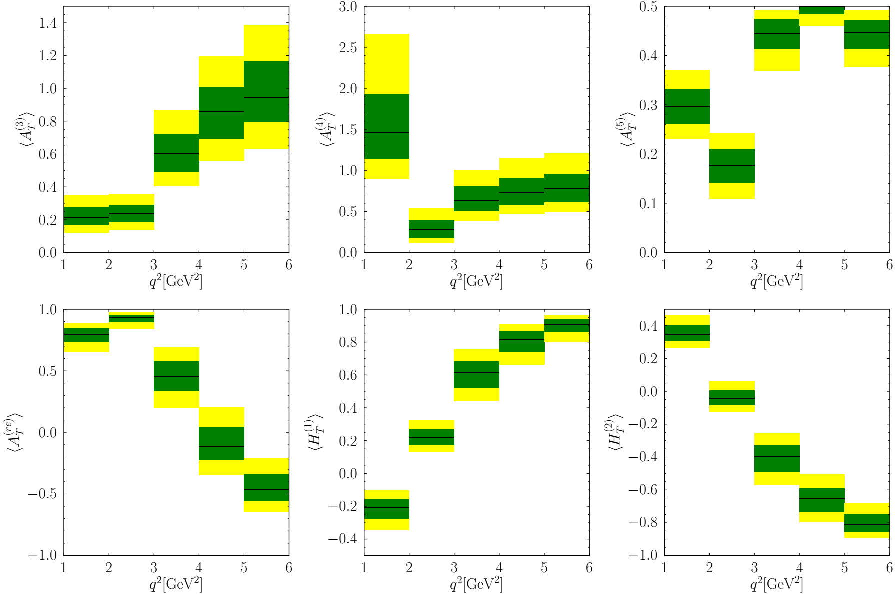
SM = (◆), best fit point = (×)



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

⇒ fit still converges

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



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

Low-q^2 = Large Recoil

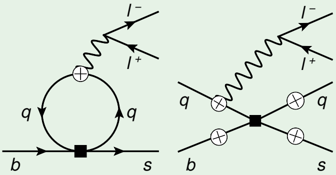
QCD Factorisation (QCDF)

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

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

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

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

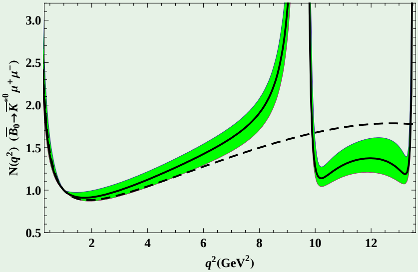


$C_a^{(i)}$, $T_a^{(i)}$: perturbative kernels in α_s ($a = \perp, \parallel$, $i = u, t$)

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

$c\bar{c}$-contributions

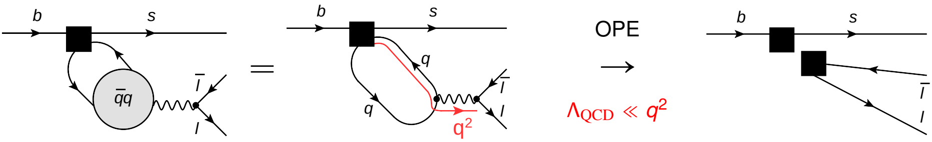
[Khodjamirian/Mannel/Pivovarov/Wang arXiv:1006.4945]



- OPE near light-cone incl. soft-gluon emission (non-local operator) for $q^2 \leqslant 4$ GeV^2 $\ll 4 m_c^2$
- 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

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

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

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

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