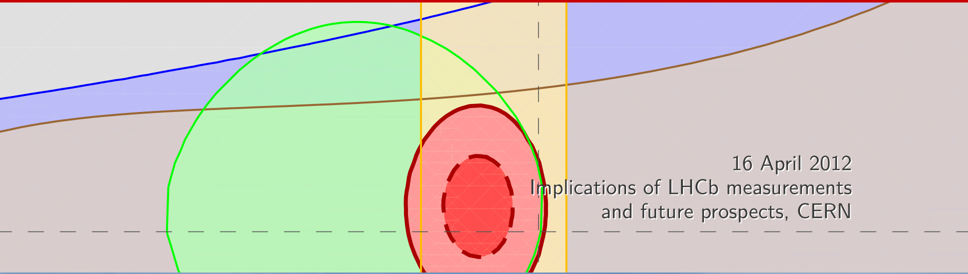
Updated constraints on new physics in rare B decays

David M. Straub
Scuola Normale Superiore & INFN, Pisa



16 April 2012
Implications of LHCb measurements and future prospects, CERN

SCUOLA NORMALE SUPERIORE

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MARIE CURIE ACTIONS

UNILHC

Outline

Results based on
W. Altmannshofer, P. Paradisi, DMS, arXiv:1111.1257, JHEP 1202:106
+ Update arXiv:1204.xxxx

Outline

- News on $B \to K^* \mu^+ \mu^-$
- News on $B_s \to \mu^+ \mu^-$
- Updated model-independent constraints on Wilson coefficients

Similar recent studies
Bobeth, Hiller, van Dyk, Wacker, arXiv:1111.2558
Descotes-Genon, Ghosh, Matias, Ramon arXiv:1104.3342

$\Delta B = \Delta S = 1$ decays as probes of new physics

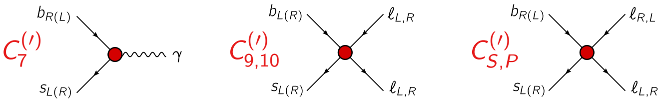
(Incomplete) list of promising radiative or semi-leptonic $b \to s$ decays

mode	interesting observables	recent exp. updates
$B \to X_s \gamma$	BR, A_{CP}	
$B \to X_s \ell^+ \ell^-$	BR, A_{FB}	
$B \to K^* \gamma$	BR, S	
$B \to K^* \mu^+ \mu^-$	BR, F_L, A_{FB}, A_9, S_3, A_7, A_8, S_5	LHCb, BaBar 2012
$B \to K \mu^+ \mu^-$	BR, F_H	CDF 2011
$B_s \to \mu^+ \mu^-$	BR	LHCb, CMS, ATLAS 2012

$b \to s$ effective Hamiltonian

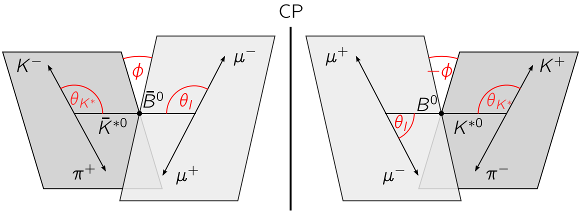
$$\mathscr{H}_{\text{eff}}^{\Delta F=1} = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \sum (C_i \mathscr{O}_i + C_i' \mathscr{O}_i')$$

Wilson coefficient — Dimension-6 operator



	mag. dipole operator	semileptonic operators	scalar operators	(neglecting: tensor op.s)
$B \to (X_s, K^*)\gamma$	X			
$B \to (X_s, K^{(*)})\ell^+\ell^-$	X	X		
$B_s \to \mu^+\mu^-$		X	X	

$B^0 \to K^{*0}(\to K\pi)\ell^+\ell^-$: a goldmine for new physics searches



$$\frac{d^4\Gamma}{dq^2\, dc_{\theta_l}\, dc_{\theta_{K^*}}\, d\phi} = \sum_{i,a} I_i^{(a)}(q^2) f(\theta_l, \theta_{K^*}, \phi) \qquad \frac{d^4\bar{\Gamma}}{dq^2\, dc_{\theta_l}\, dc_{\theta_{K^*}}\, d\phi} = \sum_{i,a} \bar{I}_i^{(a)}(q^2) \bar{f}(\theta_l, \theta_{K^*}, \phi)$$

- Angular distribution gives access to many observables
- Self-tagging decay: straightforward to extract CP asymmetries

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

1. CP asymmetries

[Krüger et al. (1999)]

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

Normalization reduces TH uncertainties

2. CP averaged observables

[Altmannshofer, Ball, Bharucha, Buras, Straub, DS, 0811.1214]

$$S_i^{(a)}(q^2) = \left(I_i^{(a)}(q^2) + \bar{I}_i^{(a)}(q^2) \right) \Big/ \frac{d(\Gamma + \bar{\Gamma})}{dq^2}$$

Note: in the case of CP averaged observables at low q^2, one can consider combinations of the $S_i^{(a)}$ with reduced dependence on form factors at LO [Matias, Mescia, Ramon, Virto (2012)]

$B \to K^* \ell^+ \ell^-$: most promising observables

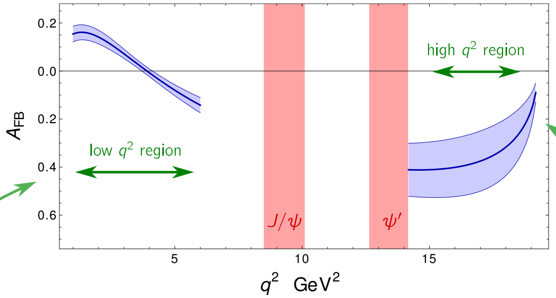
Most promising observables in the early LHC era:

	Obs.	# angles	C_i	C_i'	also known as	measured?
CP averaged obs.	F_L	1	x	x	$-S_2^c$	x
	A_{FB}	1	x		$\frac{3}{4} S_6^s$	x
	S_3	1		x	$\frac{1}{2}(1 - F_L)\, A_T^{(2)}$	x
	S_5	2	x	x		
T-odd CP asymm.	A_9	1		x	A_{im}	x
	A_7	2	x	x		
	A_8	3	x	x		

accessible from #-dimensional angular distribution

sensitive to right-handed currents

$B \to K^* \ell^+ \ell^-$: low vs. high q^2



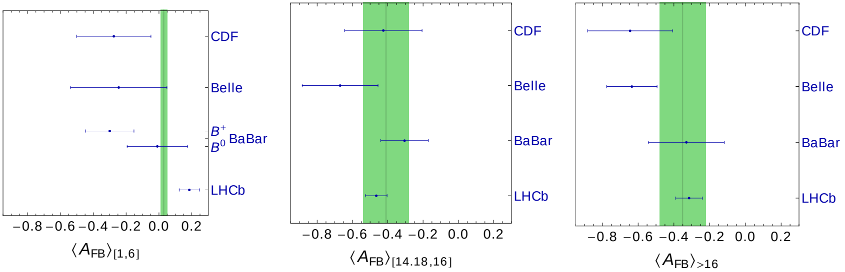
- QCDF: non-factorizable corrections to $O(\alpha_s)$
- LCSR: form factors with correlated uncertainties to all orders in Λ/m_b

[Beneke et al. (2001, 2004); Ball, Zwicky (2004); Altmannshofer et al. (2008); Khodjamirian et al. (2010)]

- OPE in powers of $\Lambda_{\text{QCD}}/\sqrt{q^2}$
- Non-perturbative corrections beyond form factors negligible
- form factors poorly known

[Grinstein, Pirjol (2004); Bharucha et al. (2008); Bobeth et al. (2010); Beylich et al. (2011)]

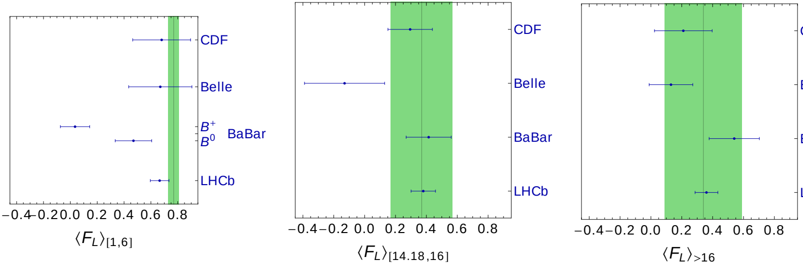
Experimental status of $A_{\rm FB}(B \to K^* \mu^+ \mu^-)$



(neglecting isospin breaking effects)

- Small tensions between BaBar and LHCb at low q^2
- At high q^2, uncertainty already dominated by theory (form factors)

Experimental status of $F_L(B \to K^* \mu^+ \mu^-)$



(neglecting isospin breaking effects)

- Some tensions between BaBar and LHCb at low q^2
- At high q^2, uncertainty already dominated by theory (form factors)

Standings in the race for $B_s \to \mu^+\mu^-$ as of today

	$10^9 \times \mathrm{BR}(B_s \to \mu^+\mu^-)$	
	@95% C.L.	1σ
D0	< 51	
CDF	< 40	18^{+11}_{-9}
ATLAS	< 22	
CMS	< 7.7	
LHCb	< 4.5	$0.8^{+1.8}_{-1.3}$
SM		3.2 ± 0.2

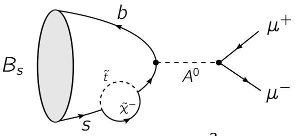
$B_s \to \mu^+\mu^-$

Two classes of new physics contributions:

$$\text{BR}(B_s \to \mu^+\mu^-) \propto \left|C_S - C_S'\right|^2 \left(1 - \frac{4m_\mu^2}{m_{B_s}^2}\right) + \left|(C_P - C_P') + \frac{2m_\mu}{m_{B_s}^2}(C_{10} - C_{10}')\right|^2$$

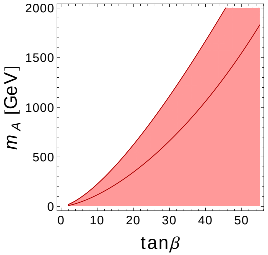
Scalar operators:
Virtually unconstrained by other processes
Can lead to huge enhancements

e.g. SUSY



$$C_S = -C_P \sim \frac{\tan^3\beta}{m_A^2}\frac{A_t}{m_{\tilde{t}}}$$

assume $\mu \sim m_{\tilde{t}}$, $A_t = \pm 2m_{\tilde{t}}$



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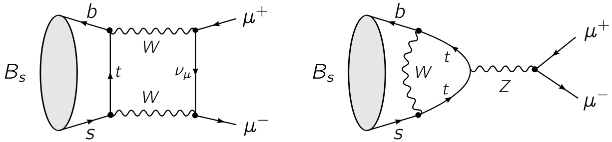
Semileptonic operators:
Only C_{10} non-zero in the SM
Constrained by $b \to s\ell^+\ell^-$
Start to be probed only now!



Constraints on Wilson coefficients

What are the allowed ranges for the Wilson coefficients?

Measurements of
experimental observables

↓

Model-independent constraints
on Wilson coefficients

↓

Constraints on parameter space
of concrete models

This talk

Altmannshofer, Paradisi, DS 1111.1257
+ Update 1204.xxxx

see also
Bobeth et al. 1111.2558, 1006.5013
Descotes-Genon et al. 1104.3342

Constraints on Wilson coefficients

What are the allowed ranges for the Wilson coefficients?

Measurements of experimental observables

↓

Model-independent constraints on Wilson coefficients

↓

Constraints on parameter space of concrete models

"Naive theorist's combination" of EXP results;
Estimation of TH uncertainties;
All uncertainties assumed Gaussian

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

This talk

Altmannshofer, Paradisi, DS 1111.1257
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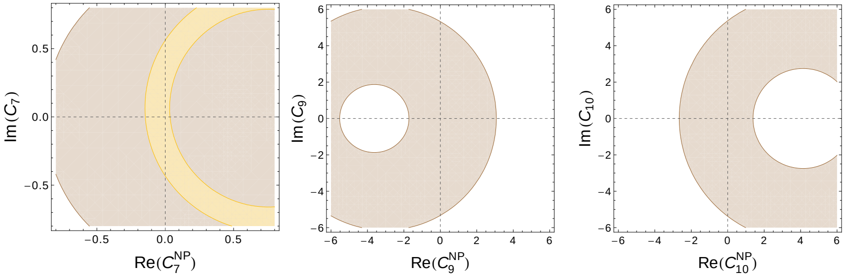
Constraints on C_7, C_9, C_{10}

Varying 1 Wilson coefficient at a time. $C_i = C_i^{\text{SM}} + C_i^{\text{NP}}$ *preliminary*



$\text{BR}(B \to X_s \ell^+ \ell^-)$ $\text{BR}(B \to X_s \gamma)$

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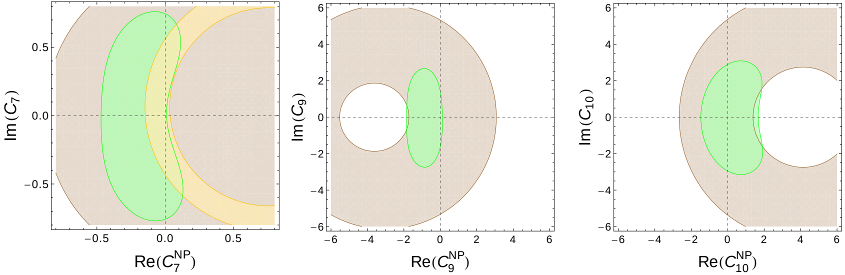

$\text{BR}(B \to X_s \ell^+ \ell^-)$ $\text{BR}(B \to X_s \gamma)$ $B \to K^* \mu^+ \mu^-$

including BR, A_{FB}, F_L, S_3, A_9 at low and high q^2

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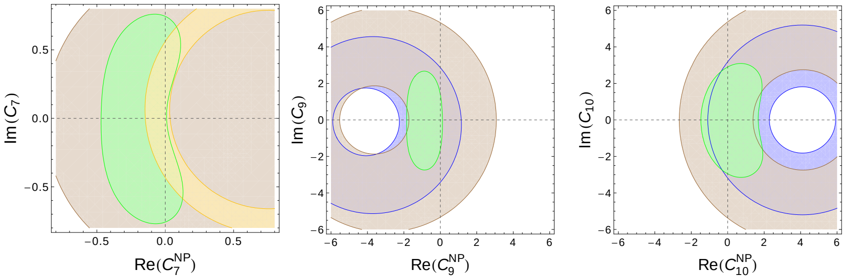

BR($B \to X_s \ell^+ \ell^-$) BR($B \to X_s \gamma$) $B \to K^* \mu^+ \mu^-$ BR($B \to K \mu^+ \mu^-$)

see Bobeth et al. (2007, 2011)

Constraints on C_7, C_9, C_{10}

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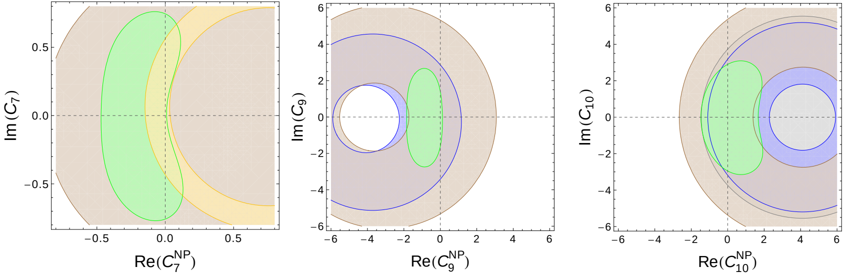

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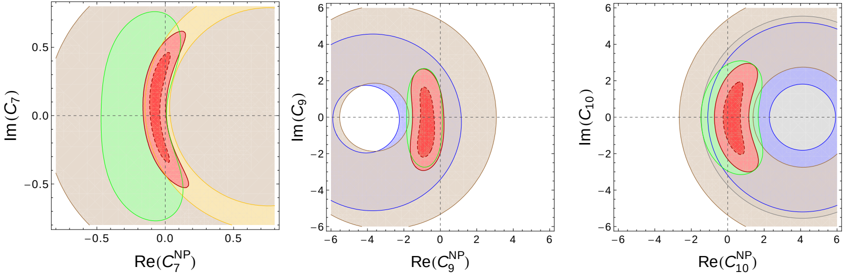


$\mathrm{BR}(B \to X_s \ell^+ \ell^-)$ $\mathrm{BR}(B \to X_s \gamma)$ $B \to K^* \mu^+ \mu^-$ $\mathrm{BR}(B \to K \mu^+ \mu^-)$ $\mathrm{BR}(B_s \to \mu^+ \mu^-)$

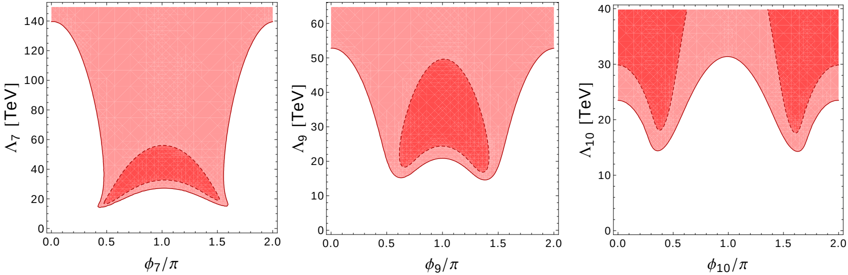
- Good agreement with SM expectations
- Complementarity between observables crucial to break degeneracies

Constraints on the NP scale

Results can be interpreted as bounds on the scale of new physics:

$$\mathscr{L} = \mathscr{L}_{\mathsf{SM}} + \sum_{j=7,9,10} \frac{e^{i\phi_j}}{\Lambda_j^2} \mathscr{O}_j$$

~tree level generic flavour violation



Constraints on the NP scale

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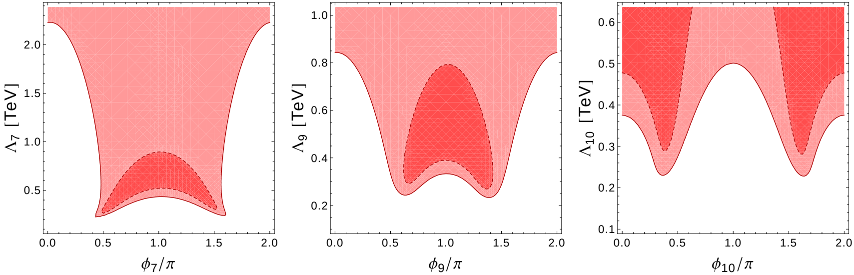
$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} - \sum_{j=7,9,10} \frac{V_{tb}V_{ts}^*}{16\pi^2} \frac{e^{i\phi_j}}{\Lambda_j^2} \mathcal{O}_j$$

~loop level CKM-like flavour violation



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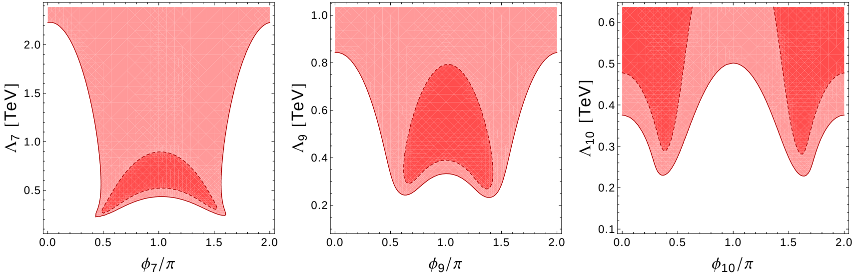


- Bounds are weaker in the presence of CP violation beyond the CKM
- Reason: only CP-averaged observables
- Measurement of CP asymmetries would be welcome

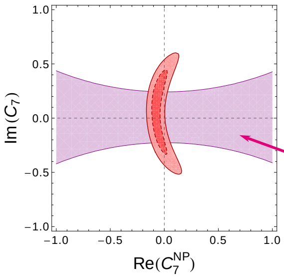
Impact of CP asymmetries

Example 1: direct CP asymmetry in $B \to X_s \gamma$

Dominated by poorly known long-distance contribution in the SM
Very limited usefulness to constrain NP [Benzke, Lee, Neubert, Paz (2010)]

Example 2: angular CP asymmetry A_7 in $B \to K^* \mu^+ \mu^-$ at low q^2

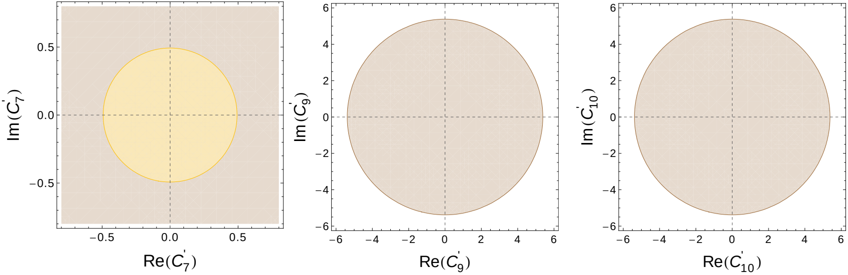
(0 in the SM, not suppressed by small strong phases)



95% C.L. from hypothetical measurement $\langle A_7 \rangle = 0 \pm 0.05$

Constraints on C_7', C_9', C_{10}'

Varying 1 Wilson coefficient at a time. $C_i' = C_i'^{\text{NP}}$ *preliminary*



$\text{BR}(B \to X_s \ell^+ \ell^-)$ $\text{BR}(B \to X_s \gamma)$

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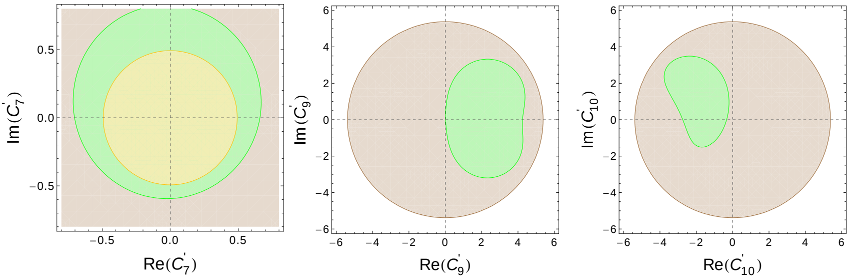

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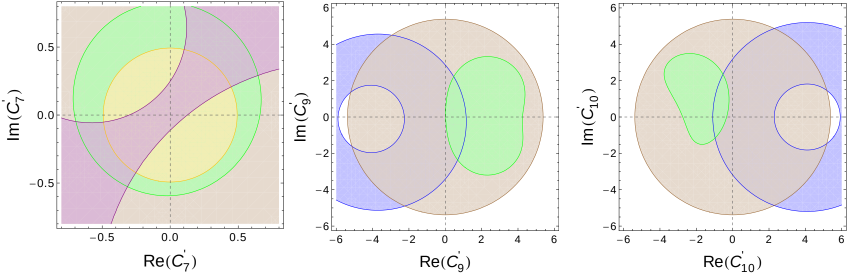

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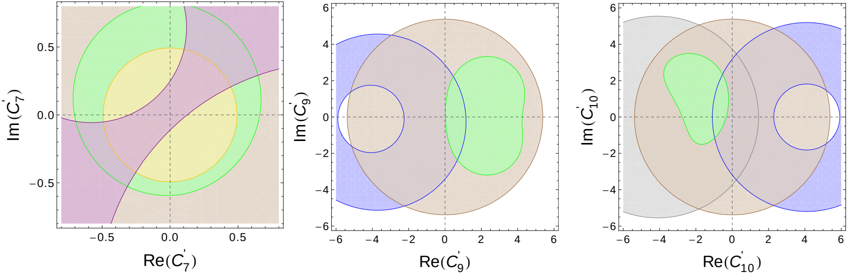
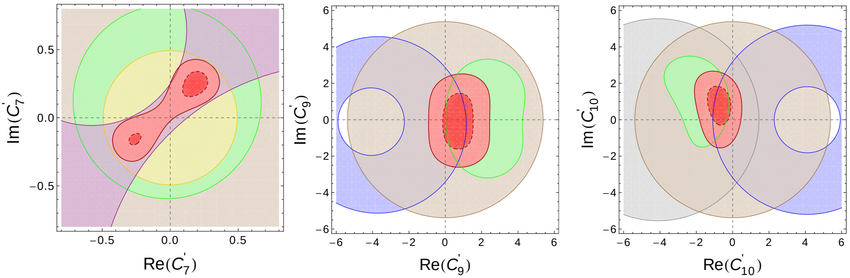


BR($B \to X_s \ell^+ \ell^-$) BR($B \to X_s \gamma$) $B \to K^* \mu^+ \mu^-$ $S_{K^*\gamma}$ BR($B \to K \mu^+ \mu^-$) BR($B_s \to \mu^+ \mu^-$)

Varying 1 Wilson coefficient at a time. $C'_i = C_i'^{\text{NP}}$ *preliminary*



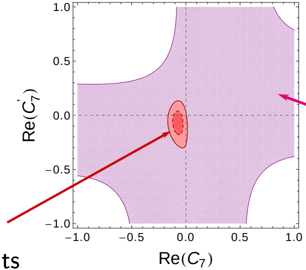
$\text{BR}(B \to X_s \ell^+\ell^-)$ $\text{BR}(B \to X_s\gamma)$ $B \to K^*\mu^+\mu^-$ $S_{K^*\gamma}$ $\text{BR}(B \to K\mu^+\mu^-)$ $\text{BR}(B_s \to \mu^+\mu^-)$

- Complementarity between $B \to K\mu^+\mu^-$ and $B \to K^*\mu^+\mu^-$ important to constrain right-handed currents

Impact of S_3

Measuring observables directly sensitive to right-handed currents:

S_3 in $B \to K^* \mu^+ \mu^-$ at low q^2
(tiny in the SM)



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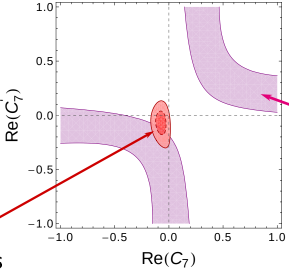
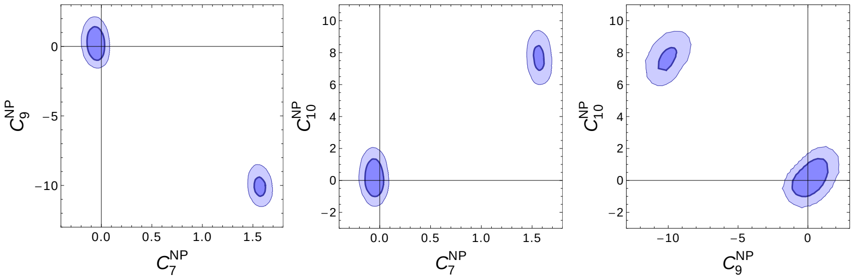


all other contstraints

95% C.L. from hypothetical measurement with current central value and $\sigma_{\text{stat}} \to 0$

Constraints on C_7 vs. C_9 vs. C_{10}

Now: allow all 3 real coefficients to vary and marginalize over the third one

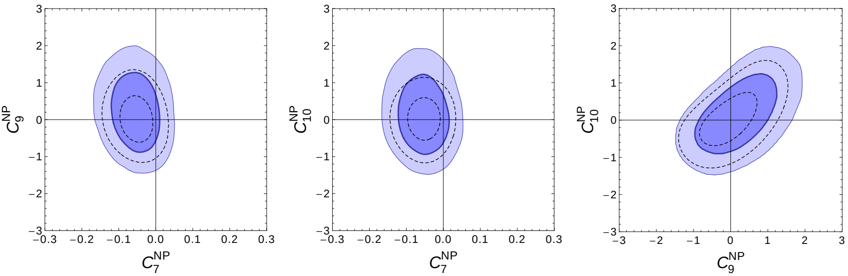


Flipped-sign solutions:

- $C_{7,9,10} = -C_{7,9,10}^{SM}$ cannot be excluded, but ...
- $C_7 = -C_7^{SM}$ disfavoured by $\mathrm{BR}(B \to X_s \ell^+ \ell^-)$ [Gambino, Haisch, Misiak (2004)]
- $C_{9,10} = -C_{9,10}^{SM}$ NEW: disfavoured by $B \to K^* \mu^+ \mu^-$ data

Constraints on C_7 vs. C_9 vs. C_{10}

Now: allow all 3 real coefficients to vary and marginalize over the third one



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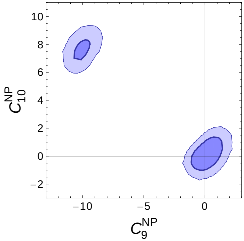
- $C_7 = -C_7^{SM}$ disfavoured by $BR(B \to X_s \ell^+ \ell^-)$ [Gambino, Haisch, Misiak (2004)]
- $C_{9,10} = -C_{9,10}^{SM}$ NEW: disfavoured by $B \to K^* \mu^+ \mu^-$ data

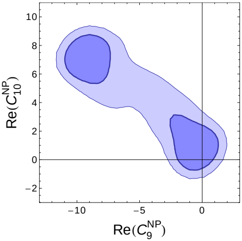
Constraints in the presence of phases

More general case with phases and/or right-handed currents: constraints weakened

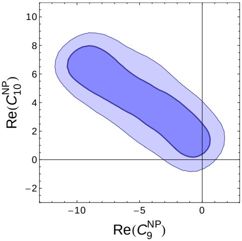
e.g. $\mathrm{Re}(C_9)$ vs. $\mathrm{Re}(C_{10})$



SM operator basis
only CKM CP violation



SM operator basis
generic CP violation



SM op. + chirality-flipped
generic CP violation

More data needed to break degeneracies
Observables directly sensitive to chirality and/or CPV

Fit predictions

95% C.L. constraints on observables to be measured/improved

preliminary

C_i	C_i'	$\text{BR}(B_s \to \mu^+\mu^-)$	$\lvert\langle A_7\rangle_{[1,6]}\rvert$	$\lvert\langle A_8\rangle_{[1,6]}\rvert$	$\lvert\langle A_9\rangle_{[1,6]}\rvert$	$\langle S_3\rangle_{[1,6]}$
$\mathbb{R}$	0	$[1.7, 4.8] \times 10^{-9}$	0	0	0	0
$\mathbb{C}$	0	$[1.1, 4.4] \times 10^{-9}$	< 0.25	< 0.14	0	0
0	$\mathbb{C}$	$[0.9, 4.5] \times 10^{-9}$	< 0.23	< 0.16	< 0.08	$[-0.04, 0.08]$
$\mathbb{R}$	$\mathbb{R}$	$< 4.6 \times 10^{-9}$	0	0	0	$[-0.07, 0.14]$
$\mathbb{C}$	$\mathbb{C}$	$< 4.3 \times 10^{-9}$	< 0.34	< 0.21	< 0.13	$[-0.07, 0.13]$

← $B \to K^* \mu^+ \mu^-$ →

Summary

- Recent precise measurements of $B \to K^{(*)}\mu^+\mu^-$, $B_s \to \mu^+\mu^-$ show **good agreement with the SM** and set **strong bounds on NP**
- Improved NP sensitivity in $B \to K^*\mu^+\mu^-$ at **high** q^2 requires progress on form factors
- Complementarity between $B \to K^*\mu^+\mu^-$ and $B \to K\mu^+\mu^-$ important to probe right-handed currents. Waiting for **LHCb measurement** of BR($B \to K\mu^+\mu^-$)
- Waiting for improved measurements of observables sensitive to **chirality/CP** violation

  $A_{7,8,9}(B \to K^*\mu^+\mu^-)$, $S_3(B \to K^*\mu^+\mu^-)$, $S_{K^*\gamma}$, ...

extra slides

$\mathscr{H}_{\text{eff}}$

$$\mathscr{H}_{\text{eff}}^{\Delta F=1} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum (C_i \mathscr{O}_i + C_i' \mathscr{O}_i')$$

$$O_7 = \frac{m_b}{e} (\bar{s}\sigma_{\mu\nu} P_R b) F^{\mu\nu} ,$$

$$O_8 = \frac{g m_b}{e^2} (\bar{s}\sigma_{\mu\nu} T^a P_R b) G^{\mu\nu\, a} ,$$

$$O_9 = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell) ,$$

$$O_{10} = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell) ,$$

$$O_S = m_b (\bar{s} P_R b)(\bar{\ell}\ell) ,$$

$$O_P = m_b (\bar{s} P_R b)(\bar{\ell}\gamma_5 \ell) ,$$

$$C_7^{\text{eff}}(\mu_b) = -0.304 ,$$

$$C_9(\mu_b) = 4.211 ,$$

$$C_{10}(\mu_b) = -4.103 ,$$

$$C_7^{\text{eff}}(\mu_b) = C_7^{\text{eff,SM}}(\mu_b) + C_7^{\text{NP}}(\mu_b) ,$$

$$C_9^{\text{eff}}(\mu_b) = C_9^{\text{eff,SM}}(\mu_b) + C_9^{\text{NP}} ,$$

$$C_{10} = C_{10}^{\text{SM}} + C_{10}^{\text{NP}} ,$$

$$C_7'(\mu_b) = C_7'^{\text{NP}}(\mu_b) ,$$

$$C_{9,10}'(\mu_b) = C_{9,10}'^{\text{NP}} .$$

$(\mu_h = 160 \text{ GeV})$

$$C_7^{(\prime)\text{NP}}(\mu_b) = 0.623\; C_7^{(\prime)\text{NP}}(\mu_h) + 0.101\; C_8^{(\prime)\text{NP}}(\mu_h) .$$