

Overview of constraints on new physics in rare B decays

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

FCNC transitions: loop- and CKM-suppressed in the SM, thus **sensitive to NP**

(Incomplete) list of promising observables in $b \rightarrow s$ decays:

mode	interesting observables	future improvements
$B \rightarrow X_s \gamma$	BR, A_{CP}	SuperB, Belle II
$B \rightarrow K^* \gamma$	BR, S	LHCb
$B_s \rightarrow \phi \gamma$	BR, S	LHCb
$B \rightarrow X_s \ell^+ \ell^-$	BR, A_{FB}	SuperB, Belle II
$B \rightarrow K^* \mu^+ \mu^-$	$BR, F_L, A_{FB}, A_9, S_3, A_7, A_8, S_5$	LHCb*
$B \rightarrow K \mu^+ \mu^-$	BR, F_H	LHCb
$B_s \rightarrow \mu^+ \mu^-$	BR	LHCb*, CMS*, ATLAS

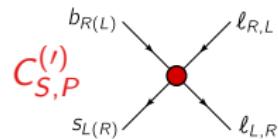
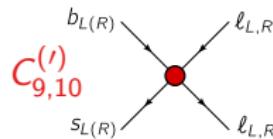
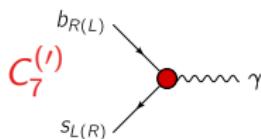
Many opportunities to probe new physics!

$b \rightarrow s$ effective Hamiltonian

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

Wilson coefficient

Dimension-6 operator



mag. dipole
operator

semileptonic
operators

scalar
operators

(neglecting:
tensor op.s)

$B \rightarrow (X_s, K^*)\gamma$

X

$B \rightarrow (X_s, K^{(*)})\ell^+\ell^-$

X

X

$B_s \rightarrow \mu^+ \mu^-$

X

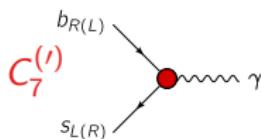
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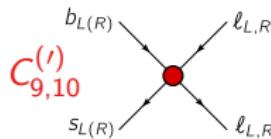
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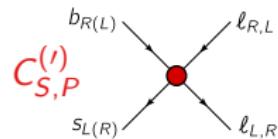
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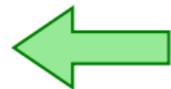
X

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$B_s \rightarrow \mu^+ \mu^-$

X

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$$B_s \rightarrow \mu^+ \mu^-$$

$$\text{BR}_{\text{SM}} = (3.2 \pm 0.2) \times 10^{-9} \quad \text{BR}_{\text{exp}} < 7.7 \times 10^{-9} \text{ @95% C.L.}$$

[CMS 2012]

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



Scalar operators:

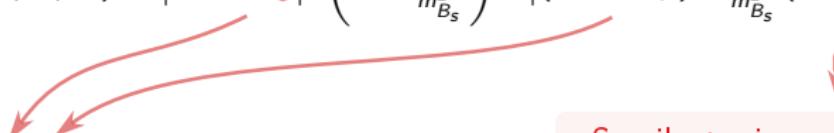
Virtually unconstrained by other processes
Can easily saturate the exp. bound

$$B_s \rightarrow \mu^+ \mu^-$$

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Semileptonic operators:

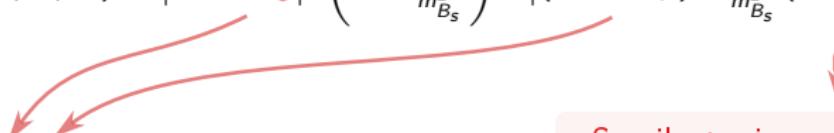
Only C_{10} non-zero in the SM
Constrained by $b \rightarrow s \ell^+ \ell^-$
Cannot saturate exp. bound

$$B_s \rightarrow \mu^+ \mu^-$$

$$\text{BR}_{\text{SM}} = (3.2 \pm 0.2) \times 10^{-9} \quad \text{BR}_{\text{exp}} < 4.5 \times 10^{-9} \text{ @95% C.L.}$$

[LHCb 2012]

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Scalar operators:

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$$\text{BR}(B_s \rightarrow \mu^+ \mu^-) \propto |\mathcal{C}_S - \mathcal{C}'_S|^2 \left(1 - \frac{4m_\mu^2}{m_{B_s}^2}\right) + |(\mathcal{C}_P - \mathcal{C}'_P) + \frac{2m_\mu}{m_{B_s}^2} (\mathcal{C}_{10} - \mathcal{C}'_{10})|^2$$

Scalar operators:

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In the following:

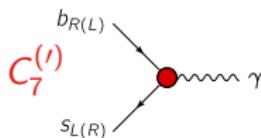
- assume $\mathcal{C}_{S,P}^{(\prime)} = 0$
- use $b \rightarrow s\gamma$, $b \rightarrow s\ell^+\ell^-$ to put model-independent constraints on $\text{BR}(B_s \rightarrow \mu^-\mu^+)$ in the absence of scalar operators

$b \rightarrow s$ effective Hamiltonian

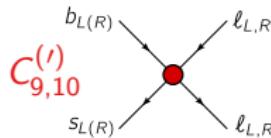
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Wilson coefficient

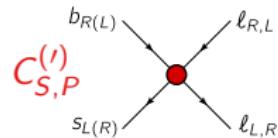
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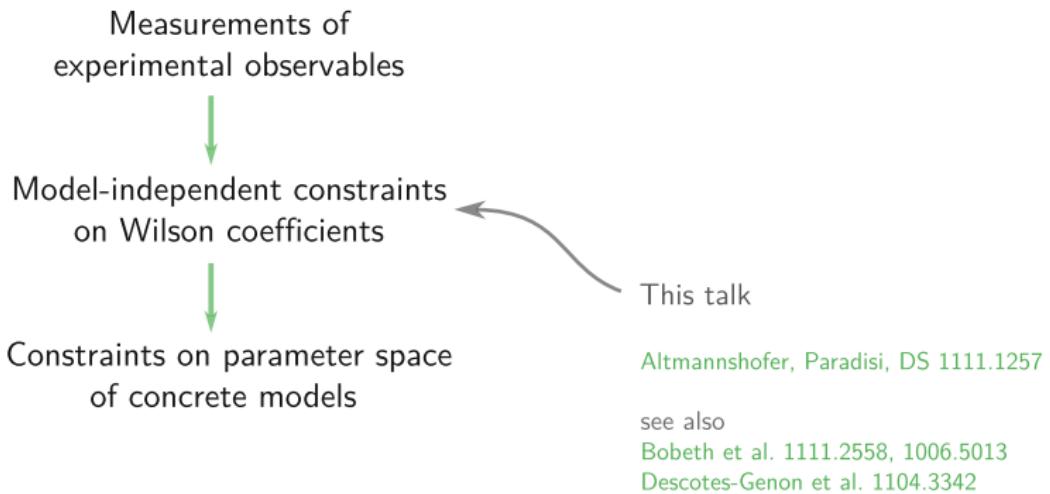
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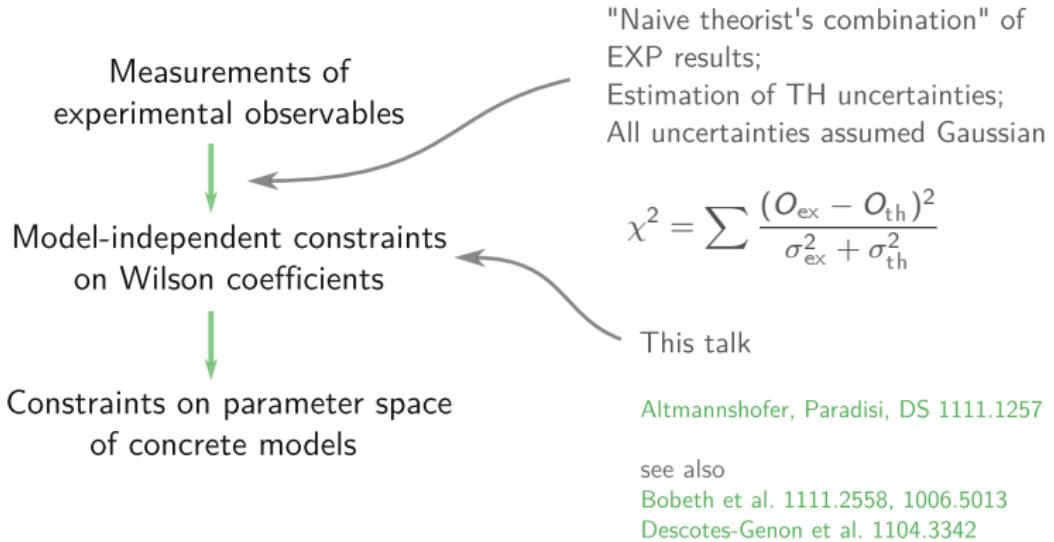
Constraints on Wilson coefficients

What are the allowed ranges for the Wilson coefficients?



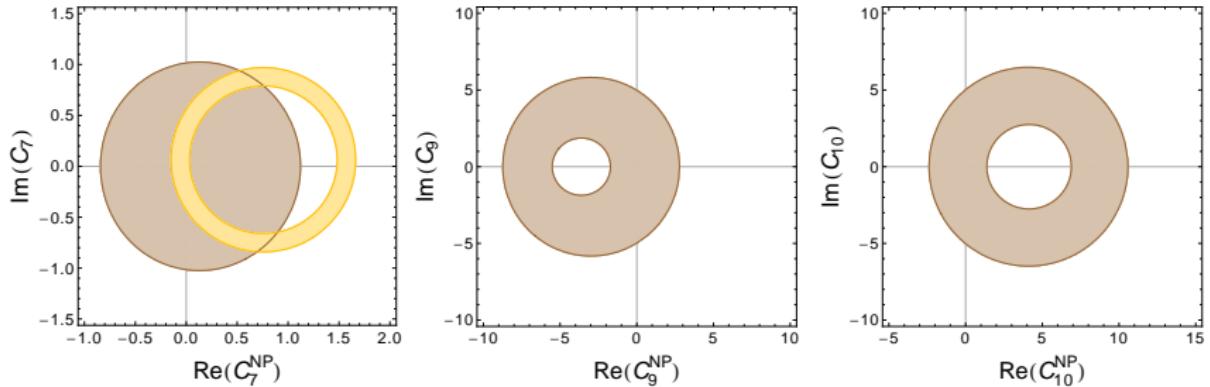
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Constraints on C_7 , C_9 , C_{10}

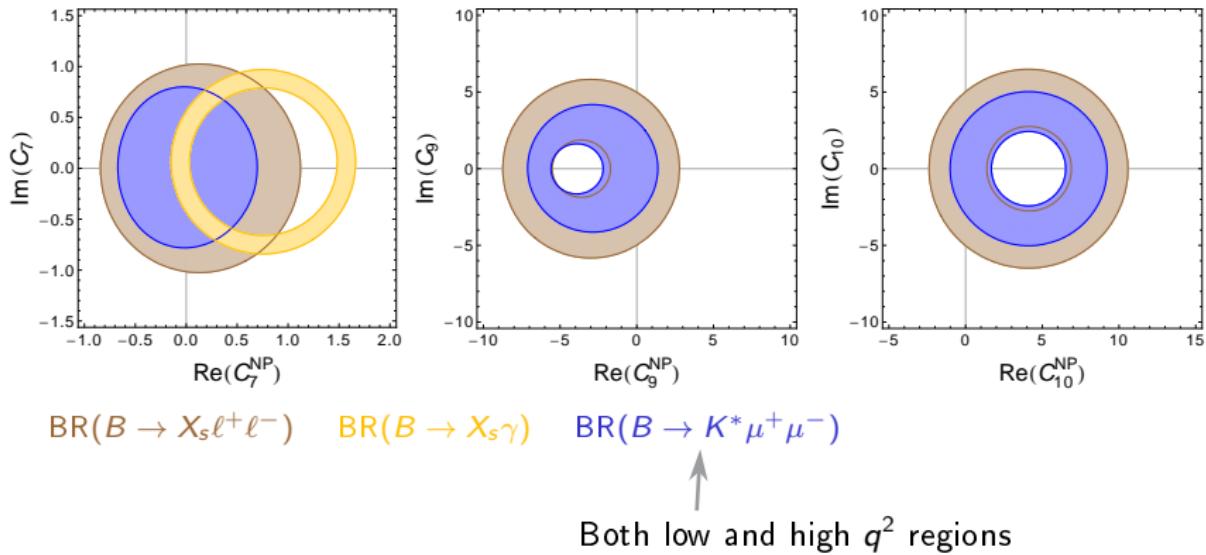
Varying 1 Wilson coefficient at a time. $C_i = C_i^{\text{SM}} + C_i^{\text{NP}}$



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

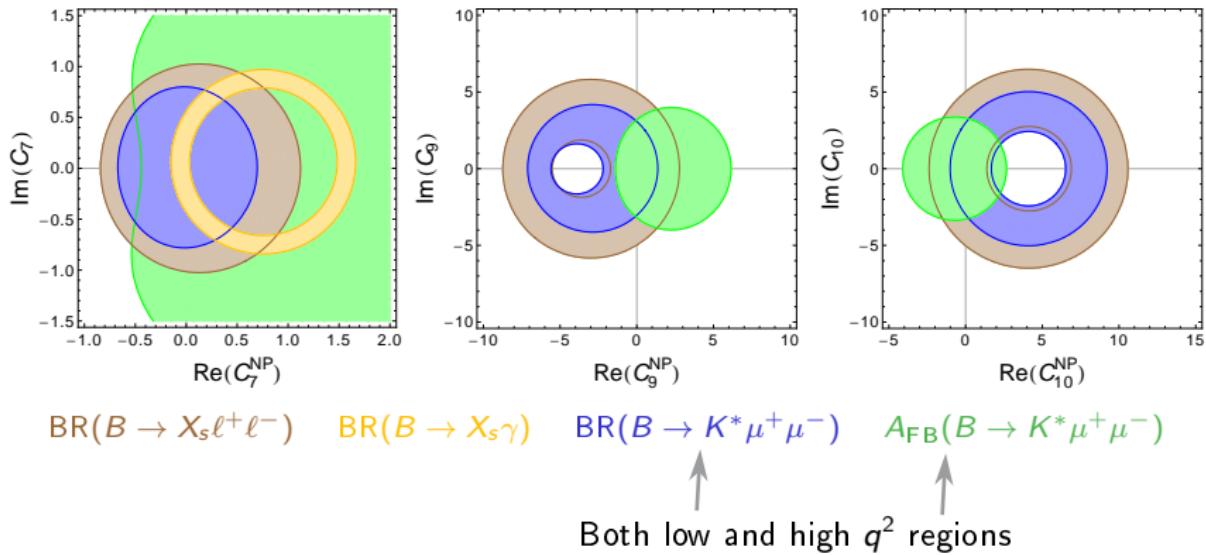
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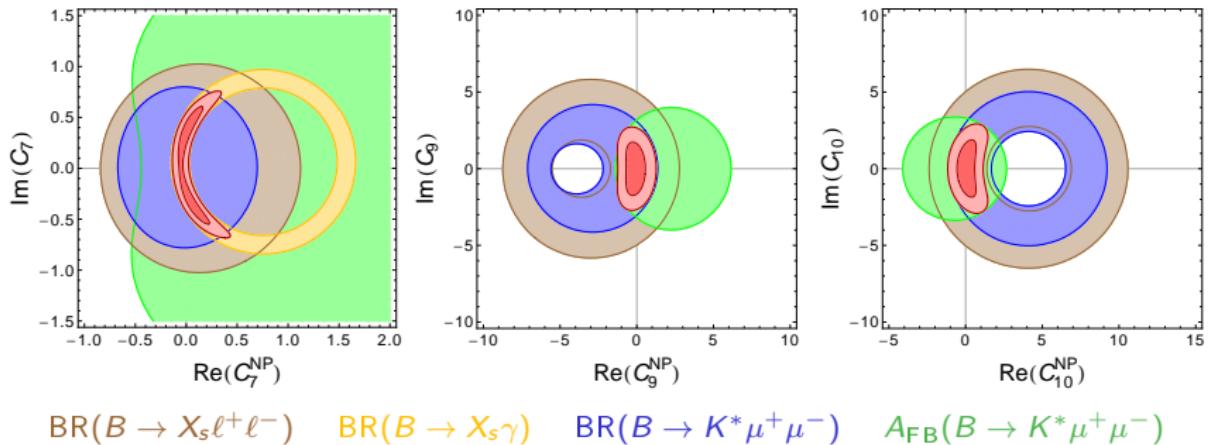
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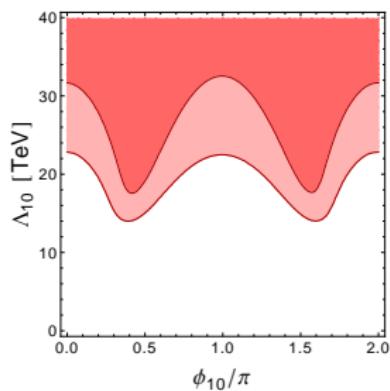
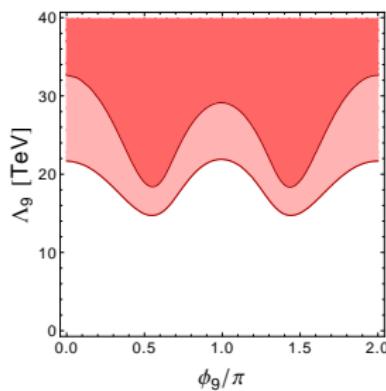
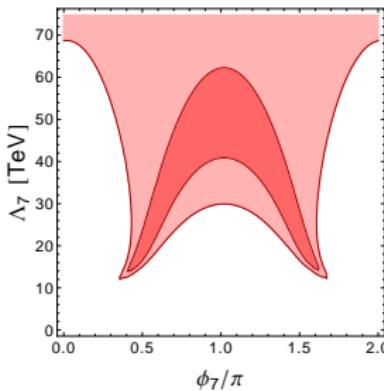
- Good agreement with SM expectations
- Complementarity between observables crucial to break degeneracies

Constraints on the NP scale

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

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

~tree level generic
flavour violation

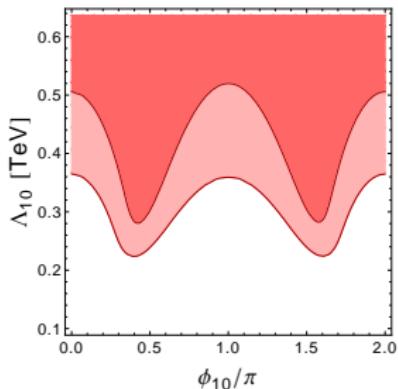
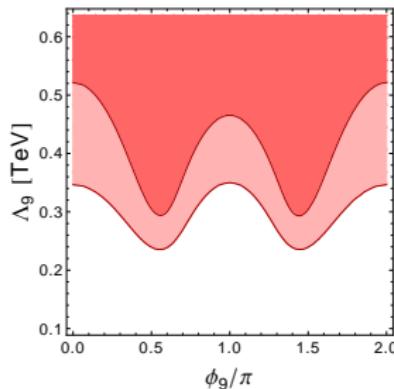
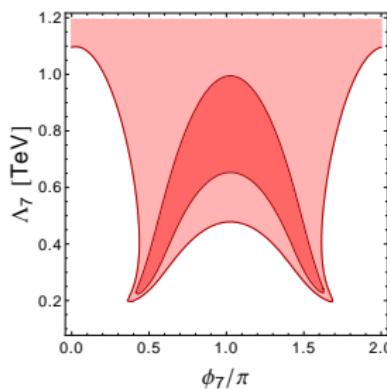


Constraints on the NP scale

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

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

~loop level CKM-like
flavour violation

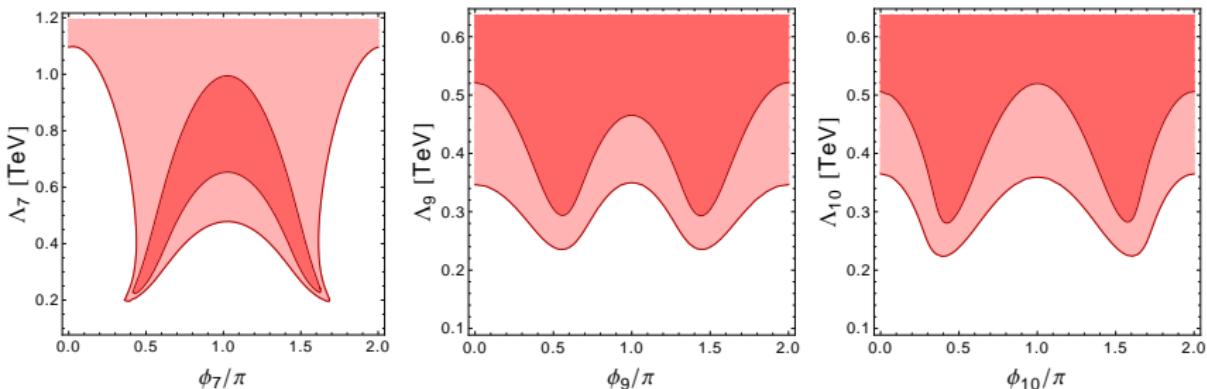


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~loop level CKM-like
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- Bounds are weaker in the presence of CP violation beyond the CKM
- Reason: only CP-averaged observables
- Measurement of CP asymmetries would be welcome

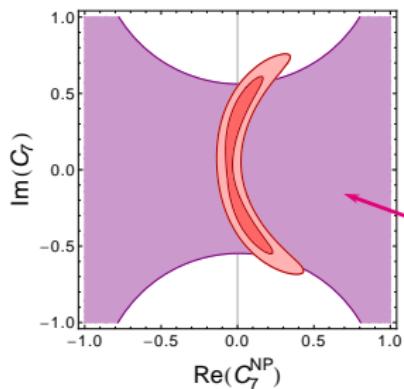
Impact of CP asymmetries

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

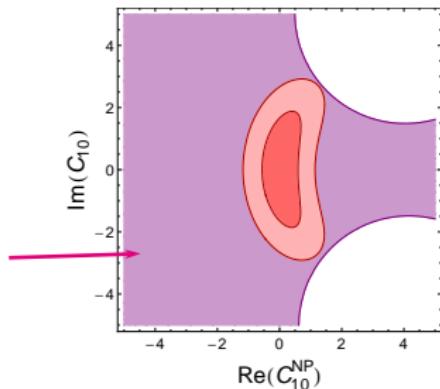
Dominated by poorly known long-distance contribution in the SM

Very limited usefulness to constrain NP [Benzke, Lee, Neubert, Paz (2010)]

Example 2: angular CP asymmetry A_7 in $B \rightarrow K^*\mu^+\mu^-$ at low q^2
(0 in the SM, not suppressed by small strong phases)



95% C.L. from
hypothetical
measurement
 $\langle A_7 \rangle = 0 \pm 0.1$



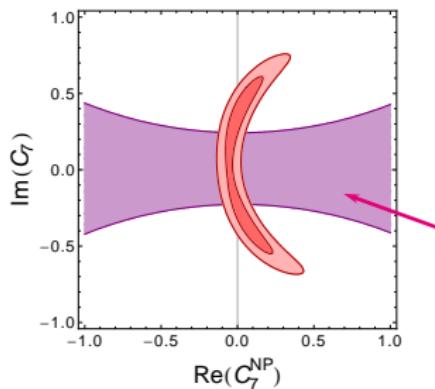
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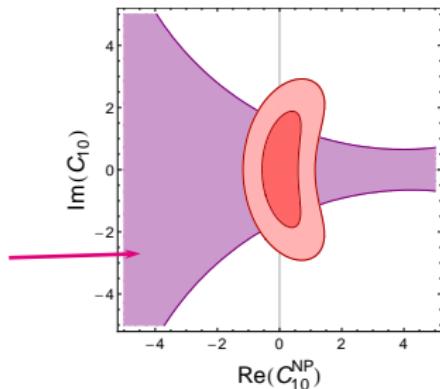
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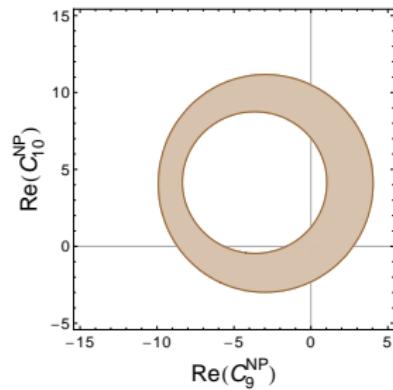
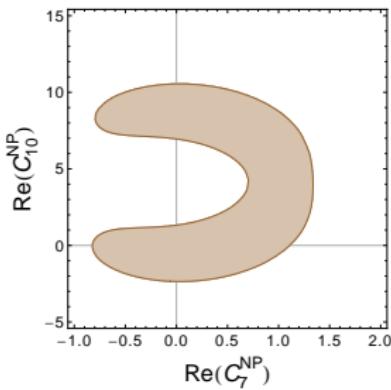
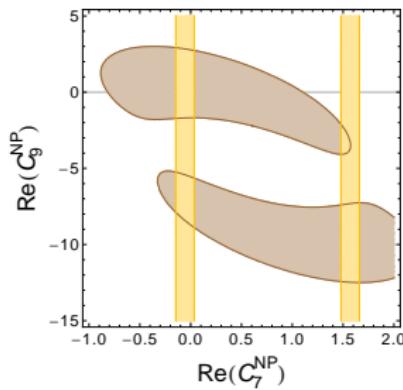
95% C.L. from
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 $\langle A_7 \rangle = 0 \pm 0.05$



- Measurement of A_7 with precision < 0.1 would give a valuable constraint
- Is it doable?

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

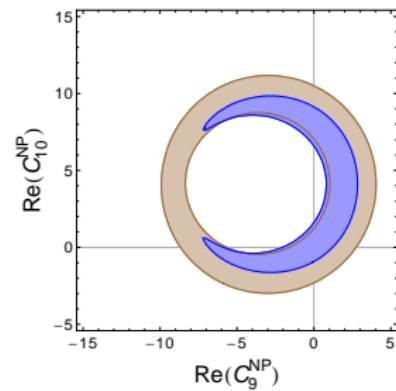
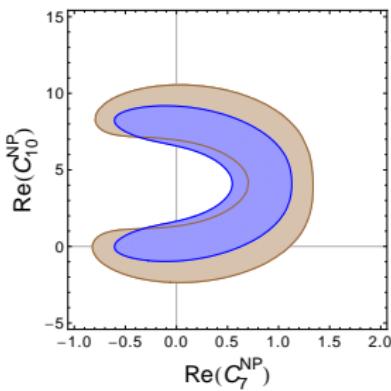
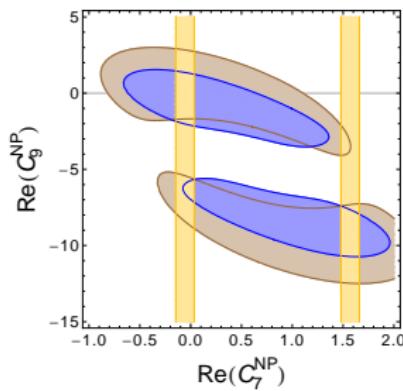
Now: correlations between 2 real Wilson coefficients



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

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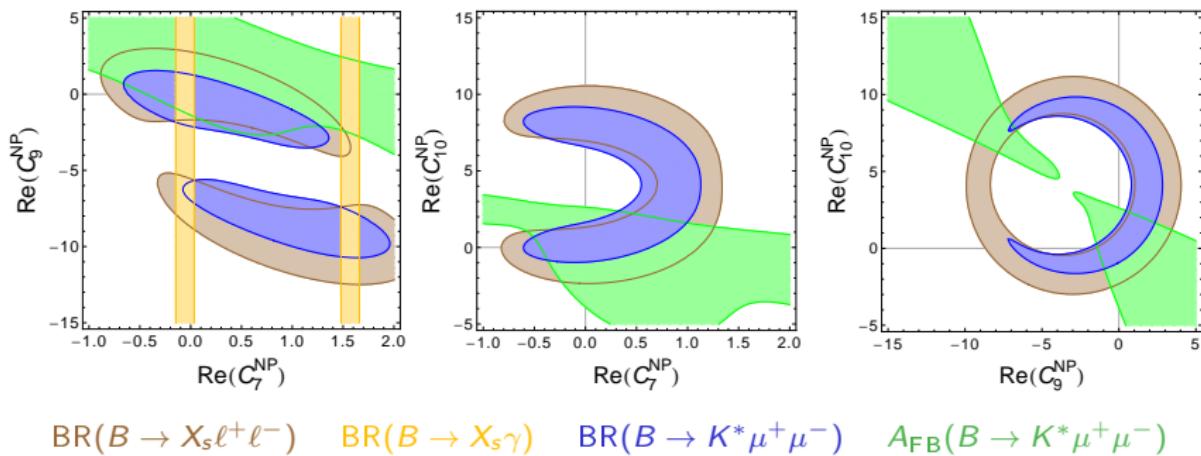
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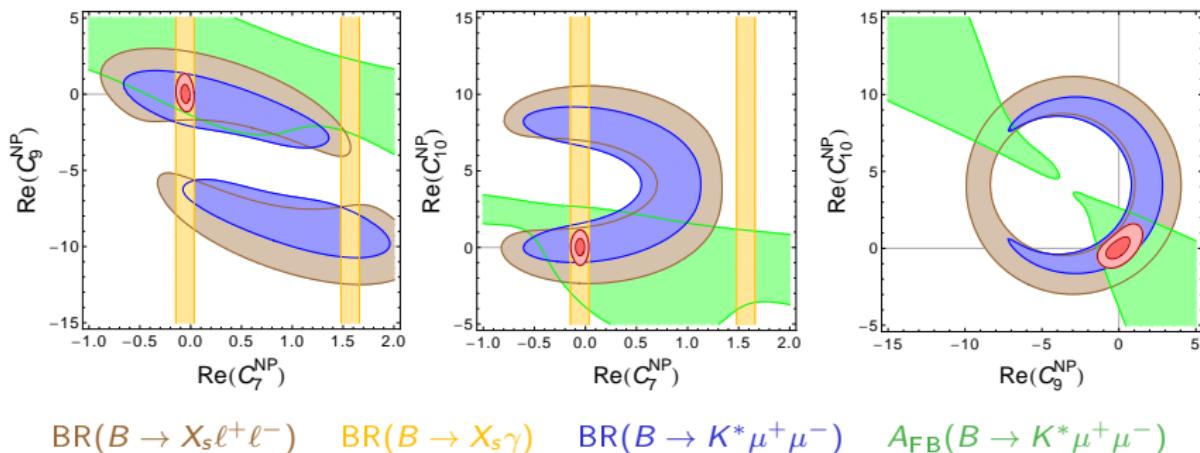
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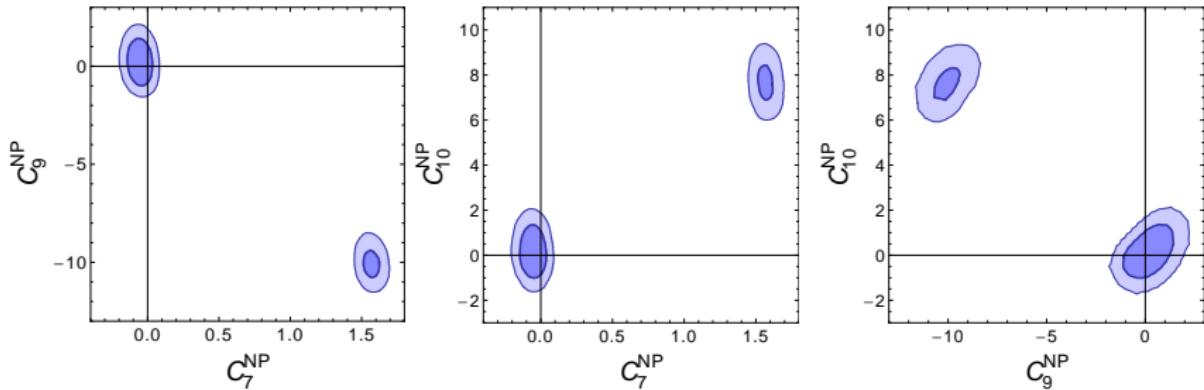
Now: correlations between 2 real Wilson coefficients



- $B \rightarrow K^* \mu^+ \mu^-$ data exclude various “mirror solutions”

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

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

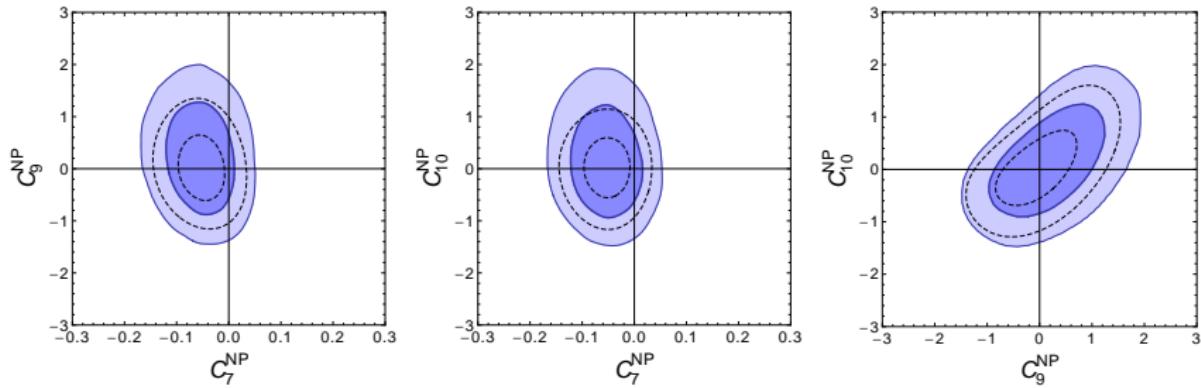


Flipped-sign solutions:

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

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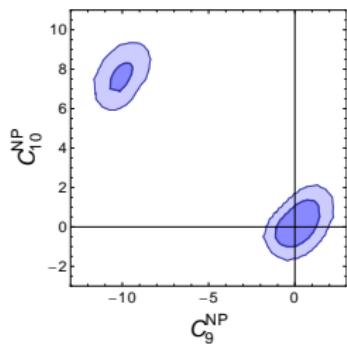
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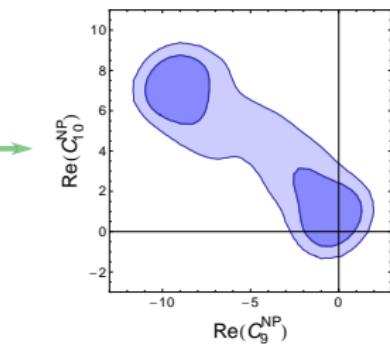
Constraints in the presence of phases

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

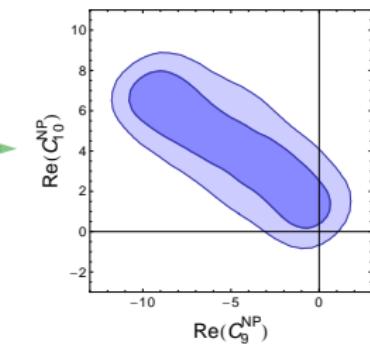
e.g. $\text{Re}(C_9)$ vs. $\text{Re}(C_{10})$



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

Scenario	$10^9 \text{ BR}(B_s \rightarrow \mu\mu)$	$ \langle A_7 \rangle $	$ \langle A_8 \rangle $	$ \langle A_9 \rangle $	$\langle S_3 \rangle$
Real LH	[1.0, 5.6]	0	0	0	0
Complex LH	[1.0, 5.4]	< 0.31	< 0.15	0	0
Complex RH	< 5.6	< 0.22	< 0.17	< 0.12	[-0.06, 0.15]
Generic NP	< 5.5	< 0.34	< 0.20	< 0.15	[-0.11, 0.18]
LH Z peng.	[1.4, 5.5]	< 0.27	< 0.14	0	0
RH Z peng.	< 3.8	< 0.22	< 0.18	< 0.12	[-0.03, 0.18]
Generic Z p.	< 4.1	< 0.28	< 0.21	< 0.13	[-0.07, 0.19]



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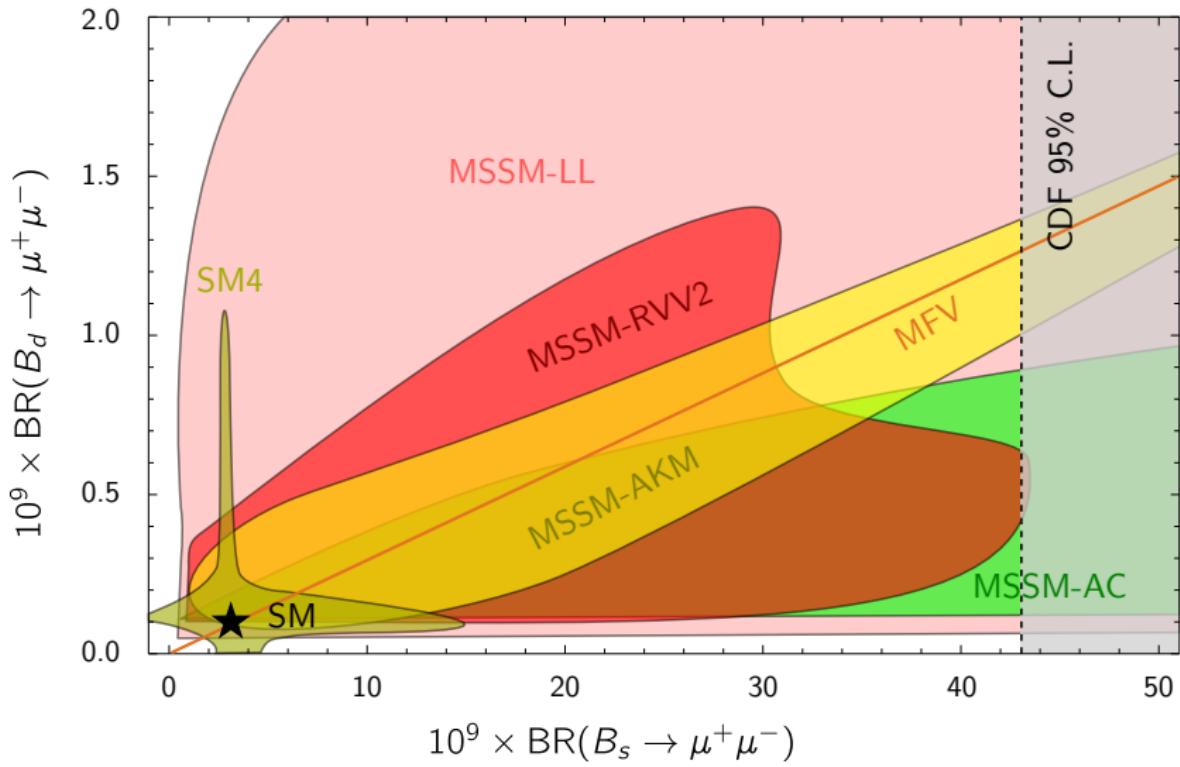
LHCb starts to probe the region accessible to models *without* scalar op.s!

Summary

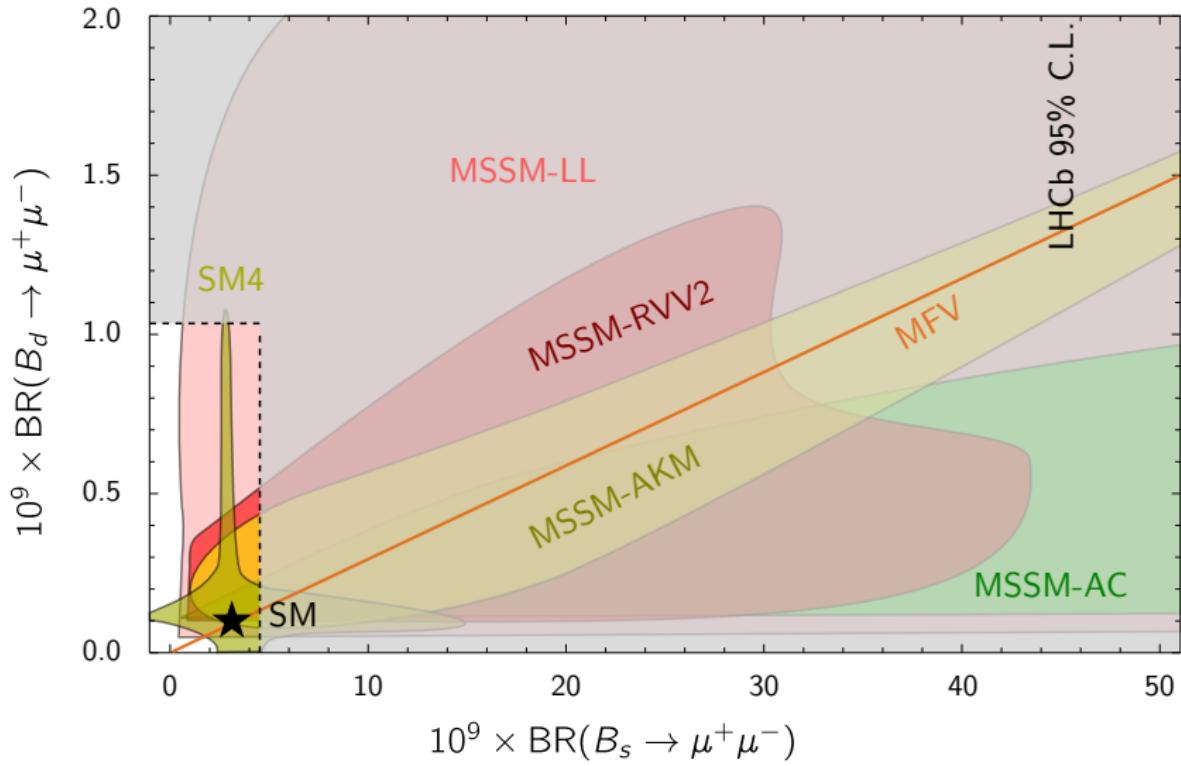
- Rare $b \rightarrow s$ decays probe flavour physics **beyond the SM**
- **Model-independent** constraints: bounds on Wilson coefficients
- At the moment, everything **consistent with SM**
- But: still **room for new physics**

- **Most constraining** observables at present:
 $\text{BR}(B \rightarrow X_s \gamma)$, angular obs. in $B \rightarrow K^* \mu^+ \mu^-$, $B_s \rightarrow \mu^+ \mu^-$, $S_{K^* \gamma}$
- **Waiting for** improved measurements of observables sensitive to chirality/CP violation
 $A_{7,8,9}(B \rightarrow K^* \mu^+ \mu^-)$, $S_3(B \rightarrow K^* \mu^+ \mu^-)$ ($\sim A_T^{(2)}$), $S_{K^* \gamma}$, ...

Then ...



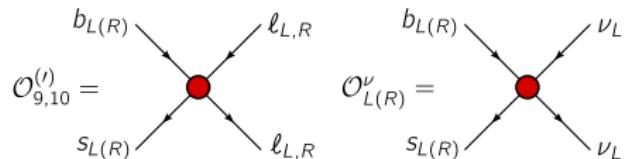
... and now



extra slides

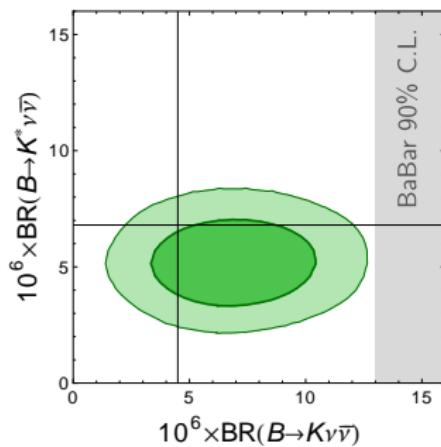
$$B \rightarrow K^{(*)} \nu \bar{\nu}$$

Semi-leptonic $b \rightarrow s\ell^+\ell^-$ operators as well as $b \rightarrow s\nu\bar{\nu}$ operators receive Z mediated contributions.



If other contributions can be neglected: correlation between $b \rightarrow s\ell^+\ell^-$ and $b \rightarrow s\nu\bar{\nu}$ decays

Fit result, generic CP violating left- and right-handed Z penguins



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

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

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

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

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

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

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

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

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

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

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

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

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

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

$$C'_7(\mu_b) = C'_7^{\text{NP}}(\mu_b),$$

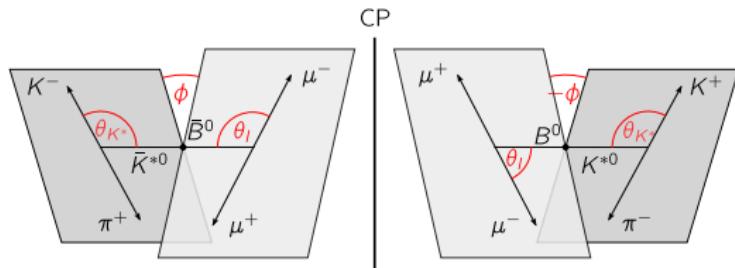
$$C'_{9,10}(\mu_b) = C'_{9,10}^{\text{NP}}.$$

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

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

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

$B \rightarrow K^*(\rightarrow K\pi) \ell^+ \ell^-$ offers a plethora of observables sensitive to new physics



$$\frac{d^4 \Gamma}{dq^2 d \cos \theta_I d \cos \theta_{K^*} d \phi} = \sum_{i,a} I_i^{(a)}(q^2) f(\theta_I, \theta_{K^*}, \phi)$$

$$S_i^{(a)}(q^2) = \left(I_i^{(a)}(q^2) + \bar{I}_i^{(a)}(q^2) \right) \Big/ \frac{d(\Gamma + \bar{\Gamma})}{dq^2} \quad \text{CP-averaged angular coefficients} \\ (\text{e.g. forward-backward asymmetry})$$

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

Plots, plots, plots

