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Flavour physics beyond the Standard Model

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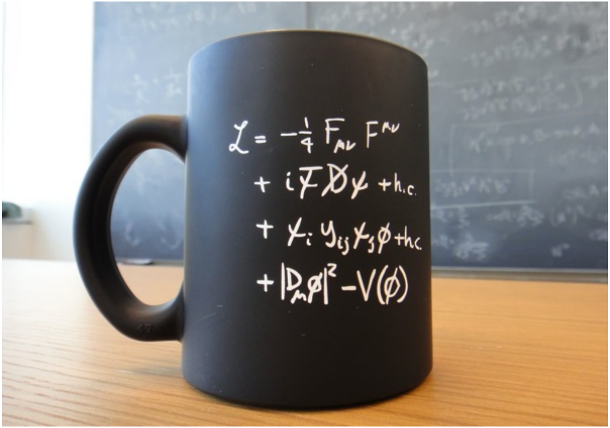
Outline

1. Introduction
   - Why physics beyond the SM?
   - Why flavour physics as a probe of BSM?
2. New physics in meson mixing
   - Model-independent discussion
   - Implications for NP models
3. New physics in rare decays
   - $B \to X_s\gamma$ and dipole operators
   - $B_s \to \mu^+\mu^-$ and scalar operators
   - $B \to K^*\mu^+\mu^-$ and new physics in $b \to s$ transitions

The Standard Model



[Photo: Ph. Tanedo, see `http://bit.ly/jw6PUh`]

Why physics beyond the SM?

We know from *observations* that physics BSM exists

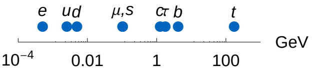
- dark matter
- neutrino masses
- baryogenesis

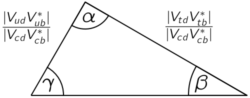
. . . and we also have strong *theoretical* reasons to expect it

- quantization of charges
- flavour puzzle
- . . .

Flavour puzzle

$$-\mathcal{L}_{\text{Yukawa}} = \bar{q}_L Y_u \tilde{H} u_R + \bar{q}_L Y_d H d_R + \bar{\ell}_L Y_\ell H e_R$$





$9 \quad + 3 \quad + 1 \quad = 13$

What is the origin of the peculiar structure of fermion masses and mixings?

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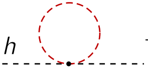
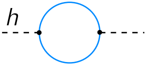
What is the scale Λ at which new physics shows up?

The gauge hierarchy problem

The Higgs mass receives contributions from all the heavy particles it couples to

$(m_h^2)_{\text{fund}}$ + 

+ 

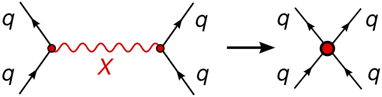
$= (m_h^2)_{\text{phys}}$

Our knowledge of the existence of the *Higgs* and of *new physics* leaves 3 options:

1. enormous fine-tuning in the fundamental high-scale parameters
2. Higgs is part of a SUSY multiplet
3. Higgs is not elementary

$\Rightarrow$ *Naturalness* requires new physics at the TeV scale!

SM as effective theory



Any new physics that is too heavy for us to produce directly (yet) can show up as a new local interaction among SM fields = a higher dimensional operator

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \sum_{d>4} \sum_i \frac{c_i}{\Lambda^{d-4}} \mathcal{O}_i^{(d)}$$

- At $D = 5$: neutrino mass term $(\bar{L}_L \epsilon H)(H^T \epsilon L_L)$
  - Needed anyway to explain neutrino oscillations
- At $D = 6$: numerous operators, including flavour-changing ones such as $(\bar{Q}_L^i \gamma^\mu Q_L^j)^2$

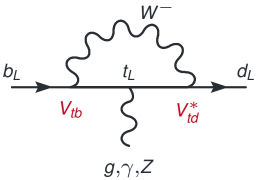
How to probe higher-dimensional operators?

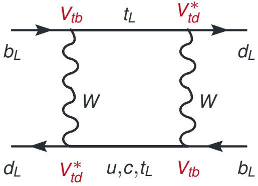
Need to look at observables that

- can be measured to an extreme precision and/or
- are suppressed in the SM but not necessarily beyond the SM

Examples

- $(g-2)_\mu$
- Electric dipole moments
- Charged lepton flavour violation
- *flavour-changing neutral currents*





FCNCs are strongly suppressed in the SM

- because they arise only at the *loop* level
- because quark mixing is so *hierarchical* (off-diagonal CKM elements $\ll 1$)
- because of the *GIM* mechanism
- because only the *left-handed* chirality participates in flavour-changing interactions

Any of these conditions could be violated by physics beyond the SM. That's why FCNCs are so important!

Bounds on the scale of new physics

[Isidori et al. 1002.0900]

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \sum_i \frac{c_i}{\Lambda^{D-4}} \mathcal{O}_i^{(D)}$$

Operator	Bounds on Λ in TeV ($c_{ij} = 1$) Re	Im	Observables
$(\bar{s}_L \gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	$\Delta m_K;\ \epsilon_K$
$(\bar{s}_R\, d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	$\Delta m_K;\ \epsilon_K$
$(\bar{c}_L \gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	$\Delta m_D;\ \lvert q/p \rvert,\ \phi_D$
$(\bar{c}_R\, u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	$\Delta m_D;\ \lvert q/p \rvert,\ \phi_D$
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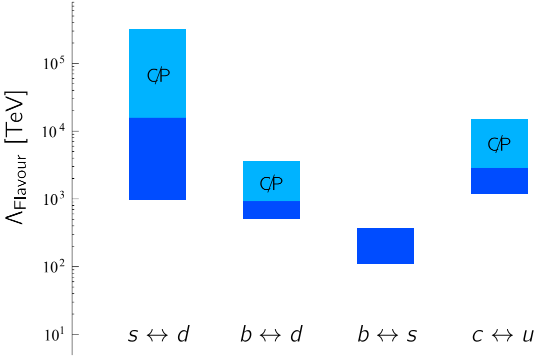

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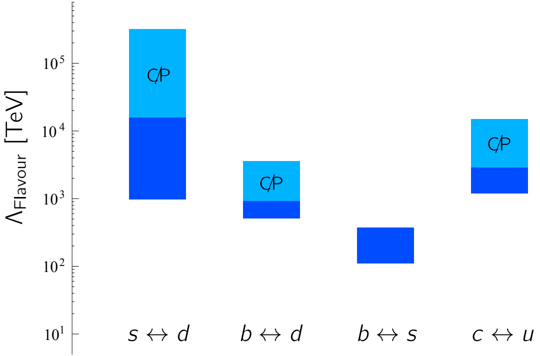
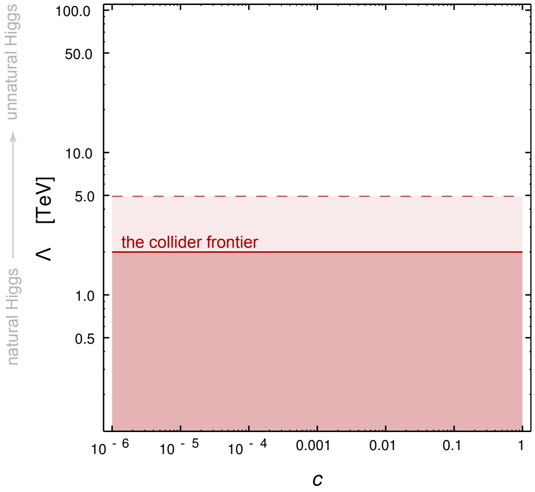


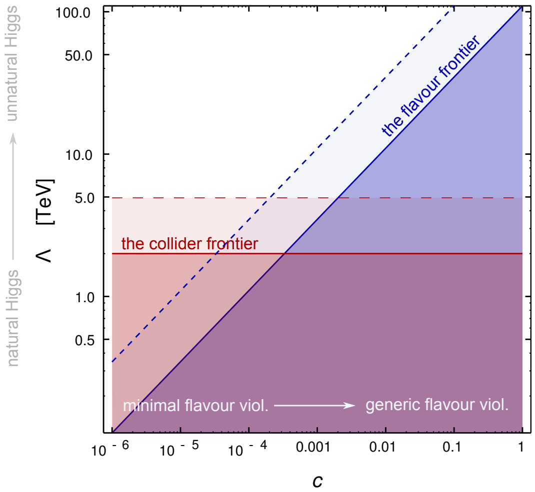
TeV-scale NP *cannot* have a generic flavur structure!

Collider vs. flavour searches



- If direct searches find new states at scale Λ, flavour physics measures the flavour couplings
- In the absence of signals in direct searches: for generic flavour violation, flavour physics probes very high scales

Collider vs. flavour searches



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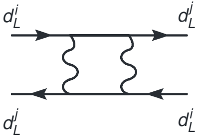
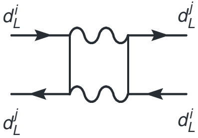
Meson-antimeson mixing in the SM

In the SM, M-$\bar{M}$ mixing proceeds via box diagrams with W exchange





and occurs in the four neutral meson systems

$$K^0 = (d\,\bar{s}) \qquad B_d^0 \equiv B^0 = (d\,\bar{b}) \qquad B_s^0 \equiv B_s = (s\,\bar{b}) \qquad D^0 = (c\,\bar{u})$$

Observables:

$$|M_{12}|, \qquad |\Gamma_{12}|, \qquad \phi$$

$\Delta F = 2$ observables sensitive to NP

- CP-violation in the K system, ϵ_K
- Mass difference and CP phase in B_d mixing, ΔM_d and ϕ_d
- Mass difference and CP phase in B_s mixing, ΔM_s and ϕ_s

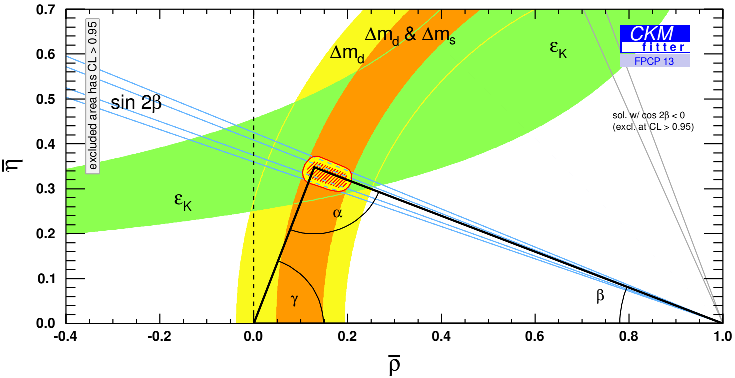
While the remaining $\Delta F = 2$ observables are long-distance dominated and/or poorly sensitive to NP.

More on NP in $\Delta F = 2$

- To constrain/discover NP, measurements have to be compared with SM predictions
- SM predictions depend on CKM elements
  - $\Delta M_d = 2|M_{12}^d| \propto |(V_{tb}V_{td}^*)^2| \approx (A\lambda^3)^2\left[(1-\rho)^2+\eta^2\right]^2$
  - $\Delta M_s = 2|M_{12}^s| \propto |(V_{tb}V_{ts}^*)^2| \approx A^2\lambda^4$
  - $\phi_d = \sin 2\beta$
  - ϵ_K more complicated dependence ...
- Identification of NP contributions requires the determination of CKM parameters

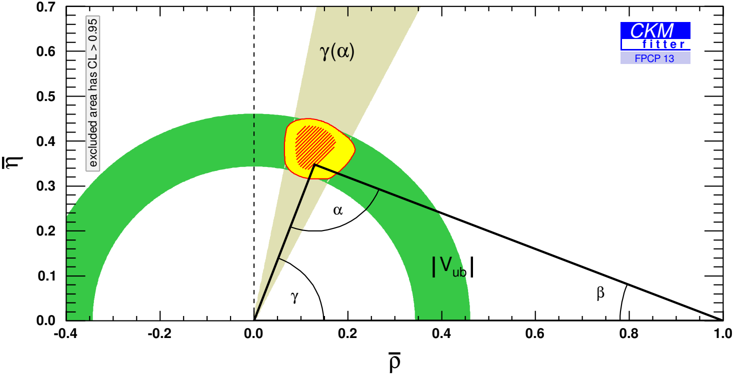
Unitarity triangle: loop vs. Tree

- "Loop" observables ($\Delta M_{d,s}$, $\sin 2\beta$, ϵ_K) can be *affected by NP*



Unitarity triangle: loop vs. Tree

- "Loop" observables ($\Delta M_{d,s}$, $\sin 2\beta$, ϵ_K) can be *affected by NP*
- "Tree" observables (V_{ub} from $b \to u\ell\nu$, γ from $b \to c\bar{u}s/u\bar{c}s$) mostly *NP-insensitive*

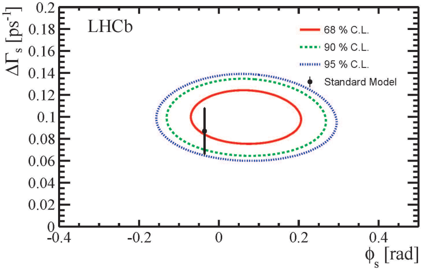


UT fit & new physics

- NP can show up as disagreement among the $\Delta F = 2$ (“loop”) observables ϵ_K, ϕ_d, $\Delta M_{d,s}$
- NP can show up as disgagreement between “loop” and “tree” observables
  - Crucial to improve the experimental determination of CKM parameters from tree only
- Uncertainties of ϵ_K, $\Delta M_{d,s}$ dominated by theory: lattice progress required to improve NP sensitivity

Special case: ϕ_s

- The B_s mixing phase is tiny in the SM
- Can be measured at LHC from the mixing-induced CP asymmetry in $B_s \to J/\psi\phi$ (and $B_s \to J/\psi\pi\pi$)



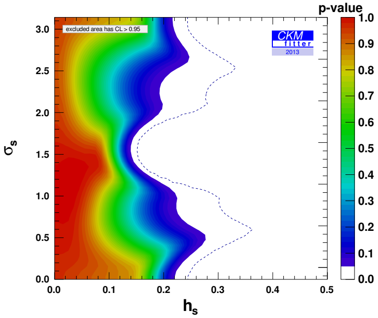
$$\phi_s^{\text{LHCb}} = +0.01 \pm 0.07$$
$$\phi_s^{\text{SM}} = -0.04$$

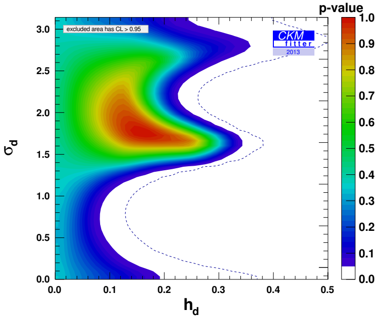
- Still room for a sizable NP contribution. Updated LHCb analysis with 2012 data much anticipated!

Allowed room for NP

NP effects can modify the mixing amplitudes. E.g., $B_{d,s}$ mixing:

$$M_{12}^d = (M_{12}^d)_{SM}(1 + h_d e^{2i\sigma_d}) \qquad M_{12}^s = (M_{12}^s)_{SM}(1 + h_s e^{2i\sigma_s})$$





Constraints as of today [Charles et al. 1309.2293]

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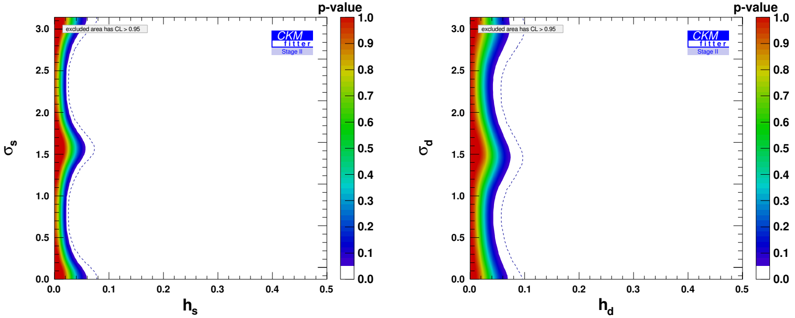

Hypothetical constraints in 10 years, assuming the SM [Charles et al. 1309.2293]

Bounds on the scale of new physics

[Isidori et al. 1002.0900]

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Implications for NP models

How to build a model of TeV-scale NP that can satisfy the strong constraints from the agreement of $\Delta F = 2$ observables with SM expecations?

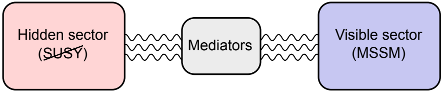
- We cannot *impose* flavour as a conserved symmetry, since it is broken already in the SM (unlike e.g. baryon number)
- The best we can do is to demand that there be *no new sources* of flavour breaking apart from the Yukawa couplings: *Minimal Flavour Violation* (MFV)
- Formally: flavour symmetry $U(3)^3 = U(3)_{q_L} \otimes U(3)_{u_R} \otimes U(3)_{d_R}$ in the quark sector broken by the spurions $Y_u \sim (3, \bar{3}, 1)$, $Y_d \sim (3, 1, \bar{3})$

Consequences of MFV for $\Delta F = 2$

- A single operator, $(\bar{Q}_L^i (Y_u Y_u^\dagger)_{ij} \gamma^\mu Q_L^j)^2 \to (\bar{d}_L^i (y_t^2 V_{ti}^* V_{tj}) \gamma^\mu d_L^j)^2$
- Suppressed by the same *CKM factors* as the SM contribution
  - NP scale can be as low as 5 TeV (tree) or 0.5 TeV (loop)
- *Universal* relative contribution to B_d, B_s and K mixing
- *No* modification of mixing *phases*

Examples of MFV models

- **Gauge mediated SUSY breaking**
  Soft terms mediated by flavour-blind gauge interactions, RG induced flavour effects are governed by the Yukawa couplings



- **Constrained MSSM**
  Flavour-blind soft terms at GUT scale assumed ad hoc. Again, RG induced effects compatible with the MFV assumption.

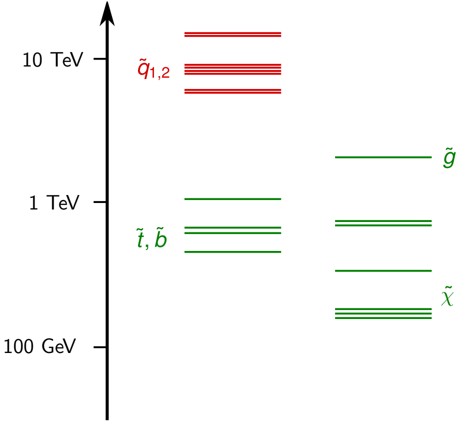
$$m^2_{\tilde{q}} = m_0 \times \mathbb{1} \qquad A_{u,d} = A_0 \times Y_{u,d}$$

NB: MFV assumption is RG invariant and can be imposed on many NP models, SUSY or non-SUSY.

Beyond MFV: the SUSY example

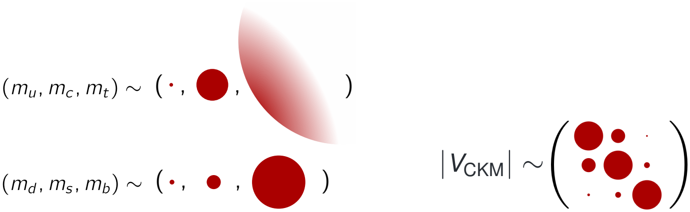
- MFV is a very strong assumption – models addressing the *flavour puzzle* typically contain new sources of flavour violation
- In the context of SUSY, it is also at variance with naturalness:
  - LHC bounds on first/second generation squarks exceed 1 TeV
  - Third generation partners should be light
  - MFV requires 3 squark generations to be approximately degenerate

A natural SUSY spectrum (in 2014)



Split families and flavour symmetry

- A hierarchy between the 3rd and the 1st/2nd family is also seen in the quark masses and mixings



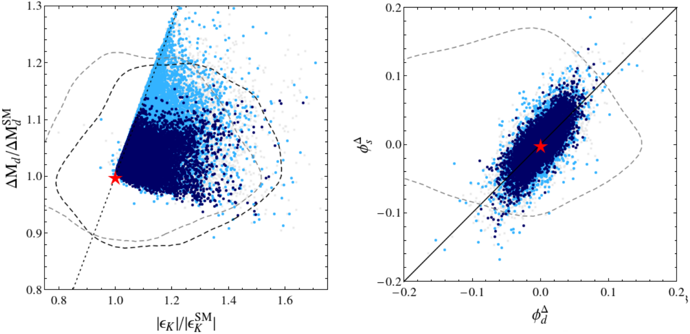
- Consider a minimally broken $U(2)^3$ symmetry (under which 3rd generation fields are singlets): natural SUSY spectrum + (partial) explanation of quark mass/mixing hierarchies [Barbieri et al. 1105.2296]

Consequences of $U(2)^3$ for $\Delta F = 2$

- Still only 1 operator and universal contribution to B_d and B_s mixing
- Universality between K and $B_{d,s}$ is broken
- Universal, non-zero contribution to the mixing phases in B_d and B_s mixing

[Barbieri et al. 1105.2296]

Scan of $\Delta F = 2$ effects in MSSM with $U(2)^3$

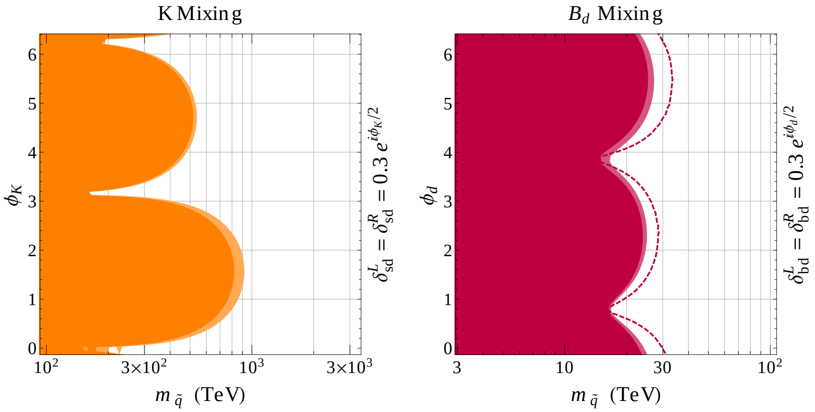


- Direct LHC constraints on sparticle masses taken into account
- Direct constraints limit the size of the effects to within the alowed regions, but visible effects in near-future measurement of ϕ_s possible

[Barbieri, Buttazzo, Sala, DS (to appear)]

Forgetting about flavour symmetries – and naturalness

For generic flavour violation, $\Delta F = 2$ observables probe very high squark mass scales (here, $m_{\tilde{g}} = 3$ TeV) [Altmannshofer et al. 1308.3653]



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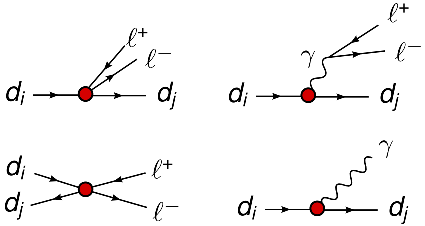
Rare B (and K) decays

- Rare decays = FCNC decays with $\Delta F = 1$
- particularly interesting: leptonic, semi-leptonic and radiative decays



Rare decays

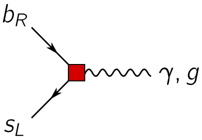
An incomplete list of rare inclusive and exclusive decays that are sensitive to the existence of physics beyond the SM

	$b \to s$ ($\propto \lambda^2$)	$b \to d$ ($\propto \lambda^3$)	$s \to d$ ($\propto \lambda^5$)
γ	$B \to X_s \gamma$	$B \to X_d \gamma$	
	$B \to K^* \gamma$	$B \to \rho\gamma$	
$\ell^+\ell^-$	$B \to K \ell^+\ell^-$	$B \to \pi \ell^+\ell^-$	$K_L \to \pi \ell^+\ell^-$
	$B \to K^* \ell^+\ell^-$	$B \to \rho \ell^+\ell^-$	
	$B \to X_s \ell^+\ell^-$	$B \to X_d \ell^+\ell^-$	
	$B_s \to \mu^+\mu^-$	$B \to \mu^+\mu^-$	$K_L \to \mu^+\mu^-$
$\nu\bar{\nu}$	$B \to X_s \nu\bar{\nu}$	$B \to X_d \nu\bar{\nu}$	$K^+ \to \pi^+ \nu\bar{\nu}$
	$B \to K \nu\bar{\nu}$		$K_L \to \pi^0 \nu\bar{\nu}$
	$B \to K^* \nu\bar{\nu}$		

Dipole operators

$$O_7 = \frac{m_b}{e}(\bar{s}_L \sigma_{\mu\nu} b_R) F^{\mu\nu}$$

$$O_8 = \frac{g_s m_b}{e^2}(\bar{s}_L \sigma_{\mu\nu} T^a b_R) G^{\mu\nu\, a}$$



- Contribute to $d_i \to d_j \gamma$ and $d_i \to d_j \ell^+ \ell^-$ transitions
- Involve a helicity flip and are therefore suppressed by m_{d_i}/m_W in the SM
- Measurement can lead to stringent constraints in models that can lift the helicity suppression, even for Minimal Flavor Violation
  - SUSY, 2HDM: chirality flip by VEV of H_u instead of H_d $\Rightarrow \tan\beta$ enhancement
  - Models with heavy fermions: chirality flip by heavy fermion mass

Magnitude of C_7

In MFV models, the strongest constraint on C_7 comes from the measurement of $B \to X_s\gamma$

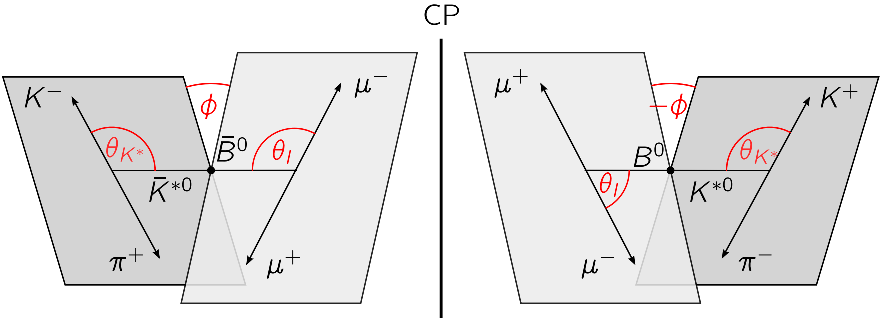
$$\mathrm{BR}(B \to X_s\gamma)_{\mathrm{exp}} = (3.43 \pm 0.22) \times 10^{-4}$$

$$\mathrm{BR}(B \to X_s\gamma)_{\mathrm{NP}} \simeq (3.14 \pm 0.22) \times 10^{-4} \times |1 + \Delta_7|^2$$

$$\Delta_7 = \frac{C_7^{\mathrm{NP}}(m_b)}{C_7^{\mathrm{SM,eff}}(m_b)}$$

$$\Rightarrow \Delta_7 \supset [-0.05, 0.14] \qquad \vee \qquad [-2.14, -1.95] \qquad (\text{at } 2\sigma)$$

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

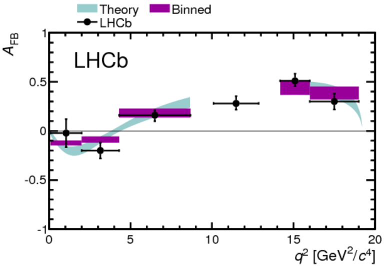


- 4-body decay: angular distribution with many observables sensitive to NP
- “self-tagging”: sensitive to CP violation

Forward-backward asymmetry

$$A_{\text{FB}}(B \to K^* \mu^+ \mu^-) = \left[\int_0^1 - \int_{-1}^0\right] d\cos\theta_l \frac{d^2(\Gamma - \bar{\Gamma})}{dq^2\, d\cos\theta_l} \Bigg/ \frac{d(\Gamma + \bar{\Gamma})}{dq^2}$$
$$\propto \text{Re}\left[\left(C_9^{\text{eff}} + \frac{2 m_b m_B}{q^2} C_7^{\text{eff}}\right) C_{10}\right]$$

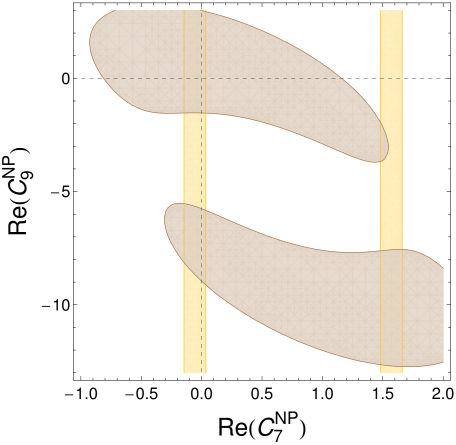
Sensitive to the sign of C_7!



LHCb 2013

[Aaij et al. 1304.6325]

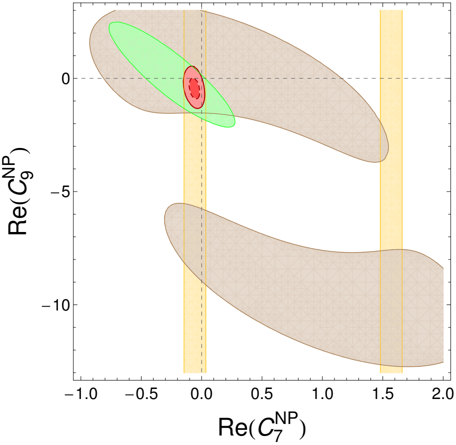
Bounds on C_7



Constraints from $B \to X_s\gamma$, $B \to X_s\mu\mu$

[Altmannshofer and DS 1206.0273]

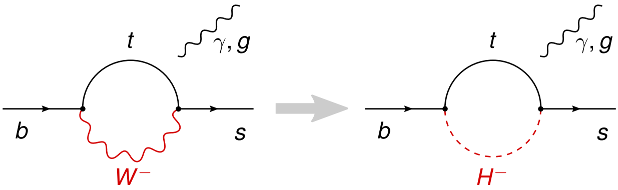
Bounds on C_7



Constraints from $B \to X_s\gamma$, $B \to X_s\mu\mu$, $B \to K^*\mu\mu$

[Altmannshofer and DS 1206.0273]

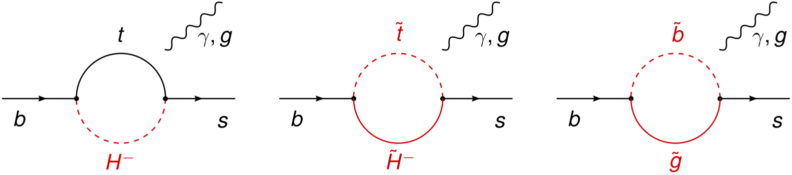
$B \to X_s\gamma$ in the two Higgs doublet model



$$\Rightarrow M_{H^\pm} \gtrsim 300 \text{ GeV}$$

[Misiak et al. hep-ph/0609232]

$B \to X_s\gamma$ in the MFV MSSM



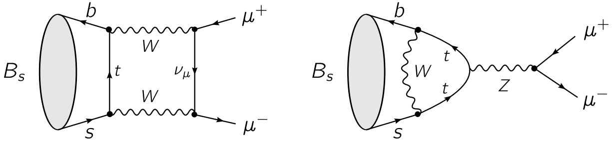
$$\propto f\left(\frac{m_t^2}{M_{H^\pm}^2}\right) \qquad \sim \frac{m_t^2}{m_{\tilde{t}}^2}\frac{A_t\mu}{m_{\tilde{t}}^2}\tan\beta \qquad \sim \frac{m_t^2}{m_{\tilde{b}}^2}\frac{M_3\mu}{m_{\tilde{b}}^2}\tan\beta\left(\frac{m_{\tilde{t}}^2 - m_{\tilde{c}}^2}{m_{\tilde{t}}^2}\right)$$

$\Rightarrow$ cancellation between various contributions makes bound more model-dependent

1. Introduction
   - Why physics beyond the SM?
   - Why flavour physics as a probe of BSM?
2. New physics in meson mixing
   - Model-independent discussion
   - Implications for NP models
3. New physics in rare decays
   - $B \to X_s\gamma$ and dipole operators
   - $B_s \to \mu^+\mu^-$ and scalar operators
   - $B \to K^*\mu^+\mu^-$ and new physics in $b \to s$ transitions

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

Strongly helicity suppressed in the SM: one of the rarest *B* decays



$$\mathrm{BR_{SM}} = (3.65 \pm 0.23) \times 10^{-9} \qquad \mathrm{BR_{exp}} = (2.9 \pm 0.7) \times 10^{-9}$$

[Bobeth et al. 1311.0903], [LHCb+CMS 2013]

Operators probed by $B_s \to \mu^+\mu^-$

$$O_{10}^{(\prime)} = (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu\gamma_5\ell)$$
$$O_S^{(\prime)} = (\bar{s}P_{L(R)} b)(\bar{\ell}\ell)$$
$$O_P^{(\prime)} = (\bar{s}P_{L(R)} b)(\bar{\ell}\gamma_5\ell)$$

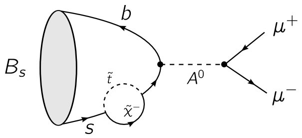
- In the SM, only C_{10} non-zero
- $C_{S,P}$ can be generated in models with extended Higgs sector (e.g. SUSY)
- C_i' require RH flavour violation and are absent in MFV models

$$\text{BR}(B_s \to \mu^+\mu^-) \propto \left[|S|^2\left(1 - \frac{4m_\mu^2}{m_{B_s}^2}\right) + |P|^2\right]$$

$$S = \frac{m_{B_s}}{2} C_S \qquad P = \frac{m_{B_s}}{2} C_P + m_\mu C_{10}$$

$B_s \to \mu\mu$ in the MSSM with MFV

Contributions to $C_{S,P}$ are generated by H^0 and A^0 exchange. In the decoupling limit ($M_{H^0,A^0} \gg m_h$) one has $C_S \simeq -C_P$

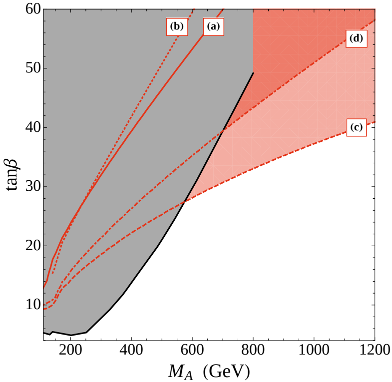


Dominant contribution: chargino-stop loop

$$C_S \simeq -C_P \propto \frac{\mu A_t}{m_{\tilde{t}}^2} \frac{m_{B_s} m_\mu}{m_A^2} \tan^3 \beta$$

Potentially huge enhancement for large $\tan\beta$

$B_s \to \mu\mu$ constrains $\tan\beta / M_A$



MFV; (a,b) $\mu A_t > 0$; (c,d) $\mu A_t < 0$

gray: $A, H \to \tau^+\tau^-$

[Altmannshofer et al. 1211.1976]

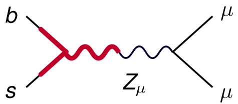
- Large $\tan\beta$ + light Higgs spectrum disfavoured
- Direct Higgs searches more constraining for $\tan\beta \lesssim 25$
- Milder bounds for $\mu A_t > 0$ (destructive interference with SM)

NB: in CMSSM, $A_t \approx 0.8 A_0 - 2.2 m_{1/2}$

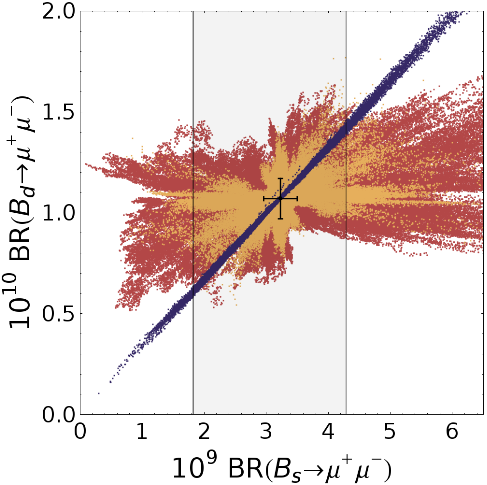
$B_s \to \mu^+\mu^-$ beyond SUSY

- Even in the absence of scalar/pseudoscalar operators, visible new physics effects can be generated in $B_s \to \mu^+\mu^-$ and $B_d \to \mu^+\mu^-$
- Example: models with partial compositeness
  - e.g. models with a composite Higgs or warped extra dimensions
  - fermion masses generated by linear mixing with composite states
- Tree-level resonance exchange generates contributions to

$$Q_{10} = (\bar{s}_L\gamma_\mu b_L)(\bar{\mu}\gamma^\mu\gamma_5\mu) \qquad Q'_{10} = (\bar{s}_R\gamma_\mu b_R)(\bar{\mu}\gamma^\mu\gamma_5\mu)$$



$B_{s,d} \to \mu^+\mu^-$ from partial compositeness



3 models with different electroweak and flavour structures (blue: model with a $U(2)^3$ symmetry)

[DS 1302.4651]

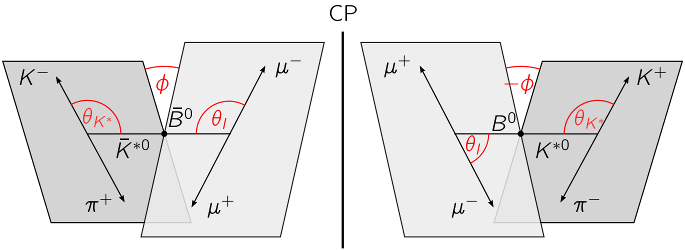
Global analysis of $b \to s$ transitions

$$O_7^{(\prime)} = \frac{m_b}{e}(\bar{s}\sigma_{\mu\nu}P_{R(L)}b)F^{\mu\nu} \quad O_9^{(\prime)} = (\bar{s}\gamma_\mu P_{L(R)}b)(\bar{\ell}\gamma^\mu\ell) \quad O_{10}^{(\prime)} = (\bar{s}\gamma_\mu P_{L(R)}b)(\bar{\ell}\gamma^\mu\gamma_5\ell)$$

- $b \to s$ operators contribute to many observables measured by B factories and/or at LHC
- global analysis necessary

Decay	$C_7^{(\prime)}$	$C_9^{(\prime)}$	$C_{10}^{(\prime)}$
$B \to X_s\gamma$	X		
$B \to K^*\gamma$	X		
$B \to X_s\mu^+\mu^-$	X	X	X
$B \to K\mu^+\mu^-$	X	X	X
$B \to K^*\mu^+\mu^-$	X	X	X
$B_s \to \mu^+\mu^-$			X

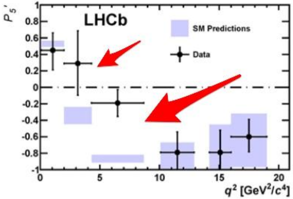
$B \to K^* \mu^+ \mu^-$



- exclusive semi-leptonic decay probing the $b \to s$ transition
- 4-body decay: angular distribution with many observables sensitive to NP
- “self-tagging”: sensitive to CP violation

9 August 2013: LHCb results hint at new physics?

The LHCb Collaboration has just published the results of a new analysis of the $B^0 \to K^{*0}\mu^+\mu^-$ decay, with $K^{*0} \to K^+\pi^-$. These results were presented three weeks ago at the European Physical Society Conference on High Energy Physics, EPSHEP, Stockholm, Sweden, and triggered very interesting discussions. The analysis of the $B^0 \to K^*\mu\mu$ decay is considered as a very promising channel to search for new physics effects, see the 14 June 2013 news for an introduction. A contribution from new physics particles could modify the angular distributions of the decay products. LHCb physicists have studied different variables related to these angular distributions as functions of the $\mu^+\mu^-$ invariant mass squared. In previously published results, no significant deviation from the Standard Model prediction has been found, see the 13 March 2012 news. In order to increase sensitivity to new physics effects LHCb physicists started to analyse additional observables (the so called P_i' observables) which are considered theoretically clean. This means that they are less sensitive than other observables to some theoretical parameters that are not precisely known (form-factors for experts). Four such observables, labelled P_4', P_5', P_6' and P_8', have been studied.



The image shows the distribution of the P_5' observable as a function of the $\mu^+\mu^-$ invariant mass squared q^2. The black data points are compared with the Standard Model prediction. A 3.7σ deviation of data above the prediction is observed for the third bin corresponding to q^2 between 4.3 and 8.68 GeV^2/c^4. Taking into account that this deviation is observed in one out of 24 bins investigated in this work (the so-called look-elsewhere effect), the significance of the deviation becomes 2.8σ.

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click the image for higher resolution

These new results are of great interest to theorists, who are combining results from several measurements to search for effects of physics beyond the Standard Model. According to Joaquim Matias from Universitat Autonoma de Barcelona and colleagues the deviation in P_5' and small discrepancies in the other angular observables for this decay, follow a pattern. In a recent paper the authors claim that a global analysis of the LHCb data, together with previous measurements, show a deviation of 4.5σ with respect to Standard Model expectations, which can be explained with the same mechanism (reduced Wilson coefficient C9 for experts). This demands further investigation, in particular to re-evaluate all the sources of theoretical uncertainty, and to understand the effects of correlations between the experimental measurements. A deep interplay between experimental and theoretical analyses will be essential to confirm or refute the pattern of new physics suggested by the $B^0 \to K^*\mu^+\mu^-$ anomaly.

[http://lhcb-public.web.cern.ch/lhcb-public/, highlights by myself]

$B \to K^*(\to K\pi)\mu^+\mu^-$ angular decay distribution

$$\frac{d^4\Gamma}{dq^2\, d\cos\theta_l\, d\cos\theta_{K^*}\, d\phi} = \frac{9}{32\pi} \times$$
$$\Big\{ I_1^s \sin^2\theta_{K^*} + I_1^c \cos^2\theta_{K^*} + (I_2^s \sin^2\theta_{K^*} + I_2^c \cos^2\theta_{K^*}) \cos 2\theta_l$$
$$+ I_3 \sin^2\theta_{K^*} \sin^2\theta_l \cos 2\phi + I_4 \sin 2\theta_{K^*} \sin 2\theta_l \cos\phi$$
$$+ I_5 \sin 2\theta_{K^*} \sin\theta_l \cos\phi + \left(I_6^s \sin^2\theta_{K^*} + I_6^c \cos^2\theta_{K^*}\right) \cos\theta_l$$
$$+ I_7 \sin 2\theta_{K^*} \sin\theta_l \sin\phi + I_8 \sin 2\theta_{K^*} \sin 2\theta_l \sin\phi + I_9 \sin^2\theta_{K^*} \sin^2\theta_l \sin 2\phi \Big\}$$

- Full set of observables: 12 angular coefficient functions $I_i(q^2)$

$B \to K^*(\to K\pi)\mu^+\mu^-$ angular decay distribution

$$\frac{d^4\Gamma}{dq^2\, d\cos\theta_l\, d\cos\theta_{K^*}\, d\phi} = \frac{9}{32\pi} \times$$

$$\Big\{ + I_2^s \sin^2\theta_{K^*}(3+\cos 2\theta_l) - I_2^c 2\cos^2\theta_{K^*}\sin^2\theta_l$$

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

$$+ I_5 \sin 2\theta_{K^*}\sin\theta_l\cos\phi + I_6 \sin^2\theta_{K^*}\cos\theta_l$$

$$+ I_7 \sin 2\theta_{K^*}\sin\theta_l\sin\phi + I_8 \sin 2\theta_{K^*}\sin 2\theta_l\sin\phi + I_9 \sin^2\theta_{K^*}\sin^2\theta_l\sin 2\phi\Big\}$$

- Full set of observables: 12 angular coefficient functions $I_i(q^2)$
- Neglecting lepton mass, scalar/tensor operators: 9 independent $I_i(q^2)$

$B \to K^*(\to K\pi)\mu^+\mu^-$ angular decay distribution

$$\frac{d^4\bar\Gamma}{dq^2\, d\cos\theta_l\, d\cos\theta_{K^*}\, d\phi} = \frac{9}{32\pi} \times$$

$$\Big\{ + \bar I_2^s \sin^2\theta_{K^*}(3+\cos 2\theta_l) - \bar I_2^c 2\cos^2\theta_{K^*}\sin^2\theta_l$$

$$+ \bar I_3 \sin^2\theta_{K^*}\sin^2\theta_l \cos 2\phi + \bar I_4 \sin 2\theta_{K^*}\sin 2\theta_l\cos\phi$$

$$- \bar I_5 \sin 2\theta_{K^*}\sin\theta_l\cos\phi - \bar I_6 \sin^2\theta_{K^*}\cos\theta_l$$

$$+ \bar I_7 \sin 2\theta_{K^*}\sin\theta_l\sin\phi - \bar I_8 \sin 2\theta_{K^*}\sin 2\theta_l\sin\phi - \bar I_9 \sin^2\theta_{K^*}\sin^2\theta_l\sin 2\phi \Big\}$$

- Full set of observables: 12 angular coefficient functions $I_i(q^2)$
- Neglecting lepton mass, scalar/tensor operators: 9 independent $I_i(q^2)$
- CP-conjugate decay: another 9 independent functions $\bar I_i(q^2)$

Basis of observables

- consider sums and differences of I_i, $\bar{I}_i$ to separate CP violating and CP conserving NP effects
- normalize to CP-averaged decay rate to reduce th. & exp. uncertainties

CP-averaged angular coefficients

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

CP asymmetries

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

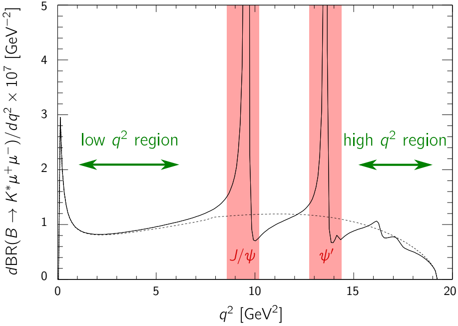
[Kruger et al. hep-ph/9907386, Bobeth et al. 0805.2525, Altmannshofer et al. 0811.1214]

Experimental status of angular observables

Observable	NP-sensitive?	measured
dBR/dq^2	yes	Belle, BaBar, CDF, *LHCb, CMS*
$F_L = -S_2^c$	yes	Belle, BaBar, CDF, *LHCb, ATLAS, CMS*
S_3	yes	CDF, *LHCb*
S_4	yes	*LHCb*
S_5	yes	*LHCb*
$A_{FB} = \frac{3}{4} S_6$	yes	Belle, BaBar, CDF, *LHCb, ATLAS, CMS*
S_7	no	*LHCb*
S_8	no	*LHCb*
S_9	no	*LHCb*
A_{CP}	no	CDF, LHCb
$A_{3...8}$	$7, 8$	–
A_9	yes	CDF, *LHCb*

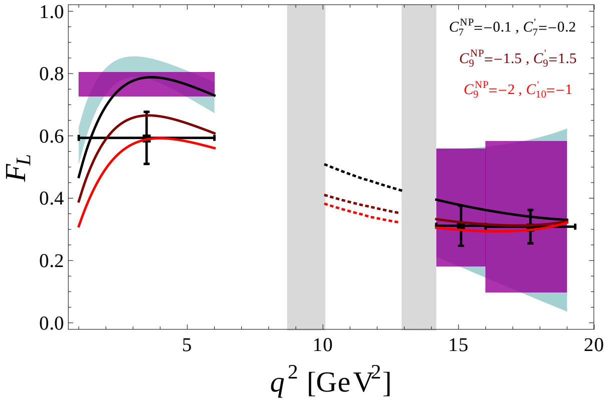
orange = updated in 2013

Kinematical regions



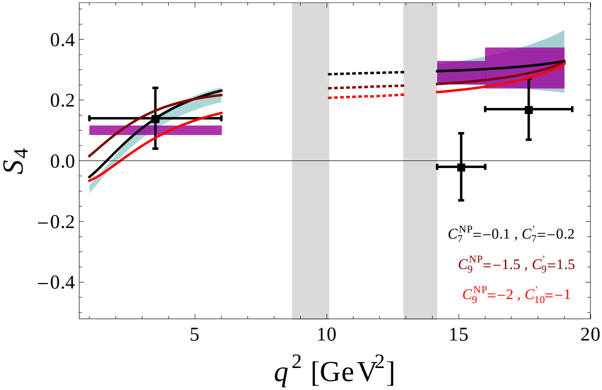
- low $q^2 \lesssim 6$ GeV^2: expansion in m_{K^*}/E_{K^*}
- intermediate $q^2 \in [6, 15]$ GeV^2: $c\bar{c}$ resonances, $B \to K^*\psi(\to \mu^+\mu^-)$
- high $q^2 \gtrsim 15$ GeV^2: expansion in $E_{K^*}/\sqrt{q^2}$

SM vs. data: F_L [Altmannshofer and DS 1308.1501]



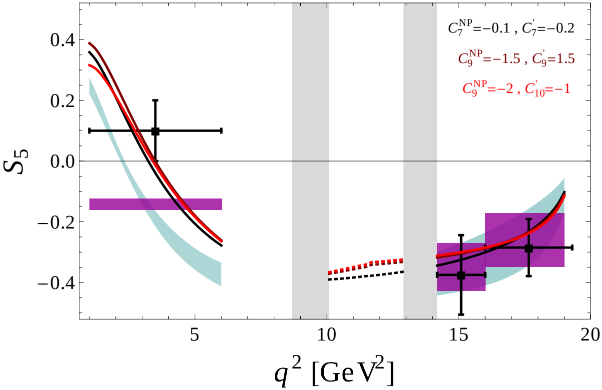
1.9σ tension at low q^2

SM vs. data: S_4 [Altmannshofer and DS 1308.1501]



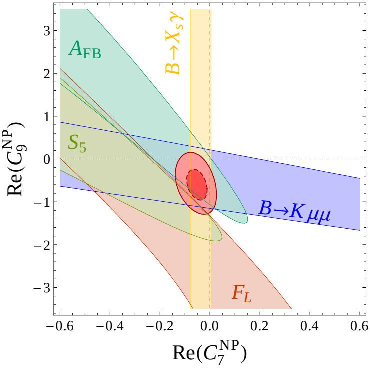
2.8σ tension at high q^2

SM vs. data: S_5 [Altmannshofer and DS 1308.1501]



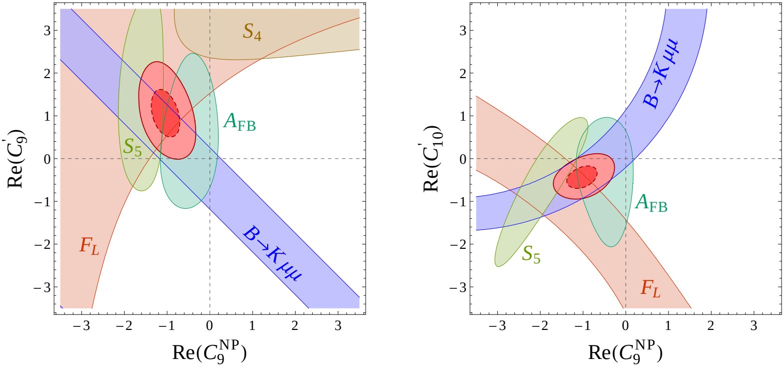
2.4σ tension at low q^2

Fitting C_7 and C_9



- Although the S_5 and F_L tensions could be solved with NP in C_7 or C_9 only, this is strongly disfavoured by the bounds from $\mathrm{BR}(B \to X_s\gamma)$ and $\mathrm{BR}(B \to K\mu^+\mu^-)$, respectively

Fitting C_9 and $C'_{9,10}$



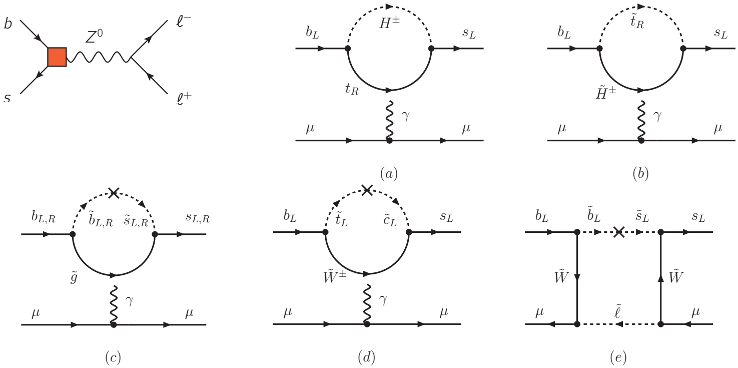
Fit results and $\Delta\chi^2$

Scenario	C_7^{NP}	C_7'	C_9^{NP}	C_9'	C_{10}'	$\Delta\chi^2(\text{SM})$
(7)	$-0.07{\pm0.04}$					3.4
(9)			$-0.8{\pm0.3}$			**4.3**
(77′)	$-0.06{\pm0.04}$	$-0.1{\pm0.1}$				4.7
(97)	$-0.05{\pm0.04}$		$-0.6{\pm0.3}$			6.0
(97′)		$-0.1{\pm0.1}$	$-0.7{\pm0.3}$			5.5
(99′)			$-1.0{\pm0.3}$	$+1.0{\pm0.5}$		**8.3**
(910′)			$-1.0{\pm0.3}$		$-0.4{\pm0.2}$	7.0
Real	-0.03	-0.11	-0.9	$+0.7$	-0.2	**10.8**

The "$B \to K^* \mu^+ \mu^-$ anomaly"

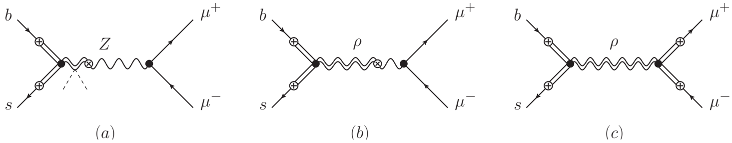
- There is a tension in some angular observables $B \to K^* \mu^+ \mu^-$ that could be due to new physics (or statistical fluctuation, or underestimated theory errors)
- If due to NP, it requires a simultaneous contribution to the Wilson coefficients C_9 and C_9' in order not to violate constraints from other processes
- Which actual NP model could explain such an effect?

1st try: MSSM



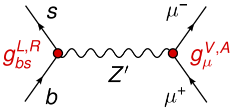
By systematically studying all relevant contributions, one can show that the effect in C_9 and C_9' is *negligible throughout the MSSM parameter space*, in particular once LHC direct bounds and other flavour constraints (B_s mixing) taken into account

2nd try: partial compositeness



- $C_9^{(\prime)}$ are generated at tree level from vector resonance exchange
- also here, contributions numerically negligible

Solving the anomaly with a Z' boson

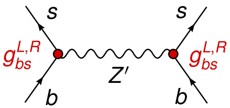


$$\mathcal{L} \supset \frac{g_2}{2c_W}\left[\bar{s}\gamma^\mu(g_{bs}^L P_L + g_{bs}^R P_R)b + \bar{\mu}\gamma^\mu(g_\mu^V + \gamma_5 g_\mu^A)\mu\right]Z'_\mu \,,$$

$$\left\{C_9^{\text{NP}}, C_9'\right\} \propto \frac{m_Z^2}{m_{Z'}^2}\left\{(g_{bs}^L)(g_\mu^V), (g_{bs}^R)(g_\mu^V)\right\}$$

[Descotes-Genon et al. 1307.5683, Altmannshofer and DS 1308.1501, Gauld et al. 1308.1959, Buras and Girrbach 1309.2466, Gauld et al. 1310.1082, Buras et al. 1311.6729]

Simultaneous contribution to B_s mixing



$$\frac{\Delta M_s}{\Delta M_s^{\rm SM}} - 1 \propto \frac{m_Z^2}{m_{Z'}^2}\left[(g_{bs}^L)^2 + (g_{bs}^R)^2 - 9.7(g_{bs}^L)(g_{bs}^R)\right]$$

- The requirement to solve the $B \to K^* \mu\mu$ anomaly + the ΔM_s constraint lead to an *upper bound* on $M_{Z'}$:

$$C_9^{\rm NP} = -1, C_9' = 1 \qquad \Rightarrow M_{Z'} < g_\mu^V \times 0.9\,\text{TeV}$$
$$C_9^{\rm NP} = -1.5 \qquad \Rightarrow M_{Z'} < g_\mu^V \times 2.0\,\text{TeV}$$

Summary

- Flavour-changing neutral currents probe physics beyond the SM in a way *complementary to the LHC* direct searches
- Finding new physics in meson mixing requires disentangling tree-level and loop-induced observables in the determination of CKM parameters
- The B_s *mixing phase* ϕ_s is a promising place to look for BSM effects
- $B_s \to \mu^+\mu^-$ *and* $B \to K^*\mu^+\mu^-$ are being measured to an unprecedented precision and are sensitive to many kinds of NP, even with MFV
- The potential *anomaly in* $B \to K^*\mu^+\mu^-$, if due to NP, requires a Z' with peculiar couplings. More data to be analyzed by LHCb very soon