STRONGnet Workshop, UAM/CSIC Madrid, 18 October 2012

Flavour and the Pursuit of New Physics

David M. Straub | Johannes Gutenberg University Mainz

Outline

1 Introduction: the role of flavour

- Flavour in the SM: a good parametrization, no explanation
- Flavour and new physics: an indirect probe of high scales

2 Hot topics in flavour physics

- K, B and B_s mixing
- Rare B and B_s decays

3 Outlook

Flavour = replication of fields

The Standard Model fermions come in 3 copies (“generations”) with the same gauge quantum numbers.

$$\begin{pmatrix} u \\ d \end{pmatrix} \qquad \begin{pmatrix} c \\ s \end{pmatrix} \qquad \begin{pmatrix} t \\ b \end{pmatrix}$$

$$\begin{pmatrix} e \\ \nu_e \end{pmatrix} \qquad \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix} \qquad \begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}$$

Flavour = replication of fields

The Standard Model fermions come in 3 copies (“generations”) with the same gauge quantum numbers.

$$q_L^i \quad u_R^i \quad d_R^i$$

$$\ell_L^i \quad e_R^i$$

$$i = 1, 2, 3$$

Flavour = replication of fields

The Standard Model fermions come in 3 copies (“generations”) with the same gauge quantum numbers.

$$q_L^i \quad u_R^i \quad d_R^i$$
$$\ell_L^i \quad e_R^i$$
$$i = 1, 2, 3$$

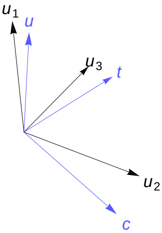
Why this triplication?

Flavour symmetry in the SM

$$\mathcal{L}_{\text{SM}} = \mathcal{L}_{\text{gauge}} + \mathcal{L}_{\text{Higgs}} + \mathcal{L}_{\text{Yukawa}}$$

- $\mathcal{L}_{\text{gauge}}$ and $\mathcal{L}_{\text{Higgs}}$ are flavour invariant

$$U(3)_{q_L} \otimes U(3)_{u_R} \otimes U(3)_{d_R} \otimes U(3)_{\ell_L} \otimes U(3)_{e_R}$$



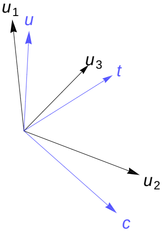
Flavour symmetry in the SM

$$\mathcal{L}_{\text{SM}} = \mathcal{L}_{\text{gauge}} + \mathcal{L}_{\text{Higgs}} + \mathcal{L}_{\text{Yukawa}}$$

- $\mathcal{L}_{\text{gauge}}$ and $\mathcal{L}_{\text{Higgs}}$ are flavour invariant

$$U(3)_{q_L} \otimes U(3)_{u_R} \otimes U(3)_{d_R} \otimes U(3)_{\ell_L} \otimes U(3)_{e_R} \to U(1)_B \times U(1)_L^3$$

- Only $\mathcal{L}_{\text{Yukawa}}$ distinguishes flavour (=breaks the flavour symmetry)



SM Yukawa couplings

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

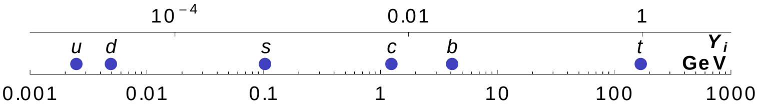
Making use of field redefinitions ($U(3)^5/U(1)$), $Y_{u,d,\ell}$ contain 13 physical parameters:

$$Y_u = V^\dagger Y_u^{\text{diag}} \qquad Y_d = Y_d^{\text{diag}} \qquad Y_\ell = Y_\ell^{\text{diag}}$$

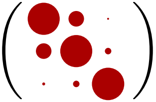
- 6 quark and 3 charged lepton masses, $m_i = v y_i/\sqrt{2}$
- 3 angles and 1 phase in the CKM matrix V

Most of the free (unpredicted) parameters of the SM (13/19) come from the Yukawa (flavour) sector

Yukawa couplings are extremely hierarchical



$|V_{\mathrm{CKM}}| \sim$



Why these hierarchies in quark masses and mixing?

CP violation requires 3 generations

Kobayashi & Maskawa 1973: CP violation from Yukawa couplings requires 3 generations (Nobel Prize 2008)

$$V \approx \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

Sakharov 1967: baryon asymmetry requires CP violation

CP violation requires 3 generations

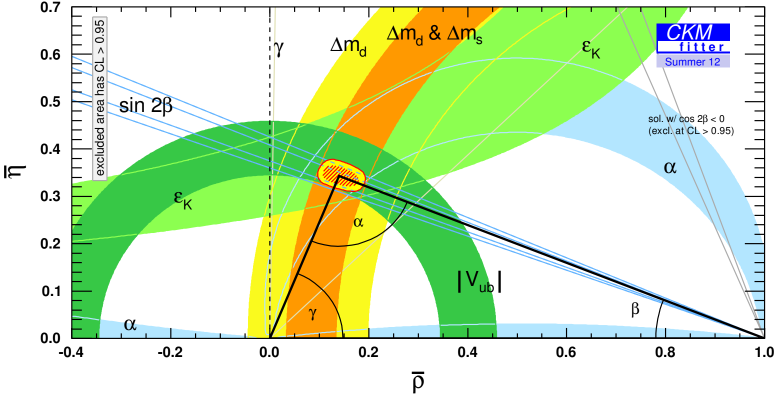
Kobayashi & Maskawa 1973: CP violation from Yukawa couplings requires 3 generations (Nobel Prize 2008)

$$V \approx \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

Sakharov 1967: baryon asymmetry requires CP violation

But the CP violation in the CKM matrix is not sufficient

Experimental status of the CKM mechanism



The CKM mechanism seems to be fundamentally at work

So:

The *parametrization* of flavour in the SM works very well – but we lack an *explanation*:

Standard Model flavour puzzle

- Why the triplication of fermion fields?
- Why the huge hierarchies in quark masses and mixing?
- Why the large baryon asymmetry if CP violation is so weak?

So:

The *parametrization* of flavour in the SM works very well – but we lack an *explanation*:

Standard Model flavour puzzle

- Why the triplication of fermion fields?
- Why the huge hierarchies in quark masses and mixing?
- Why the large baryon asymmetry if CP violation is so weak?

$\Rightarrow$ The origin of the flavour structure lies beyond the Standard Model

Unfortunately,

We have no strong reason to expect the mechanism of flavour symmetry breaking to act at accessible energy scales

Unfortunately,

We have no strong reason to expect the mechanism of flavour symmetry breaking to act at accessible energy scales

But

if there is new physics in reach, the patterns of this breaking should be visible at low energy

1 Introduction: the role of flavour

- Flavour in the SM: a good parametrization, no explanation
- Flavour and new physics: an indirect probe of high scales

2 Hot topics in flavour physics

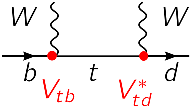
- K, B and B_s mixing
- Rare B and B_s decays

3 Outlook

Flavour-changing neutral currents

The GIM mechanism

In the SM, flavour is violated only in the W couplings, so flavour-changing *neutral* currents occur only at loop level



FCNCs are suppressed by

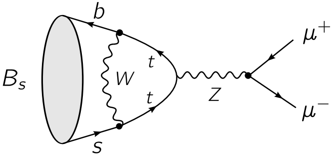
- a loop factor
- small off-diagonal CKM elements

Both the loop and the CKM suppression can be lifted beyond the SM.

Two types of FCNCs

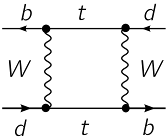
$\mathbf{\Delta F = 1}$ = rare decays

e.g.



$\mathbf{\Delta F = 2}$ = meson-antimeson mixing (K, B, B_s, D)

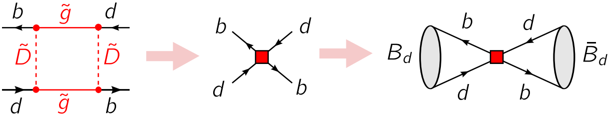
e.g.



Generic flavour violation beyond the SM

Contribution of virtual heavy particles can be described by modification of Wilson coefficients of local non-renormalizable operators

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



Bounds on the scale of new physics

[Isidori et al. 1002.0900]

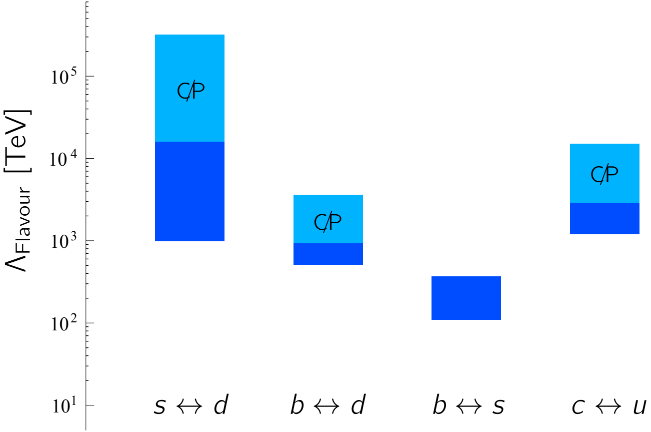
$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^{D-4}} \mathcal{O}_i^{(D)}$$

Operator	Bounds on Λ in TeV ($c_{ij} = 1$)		Observables
	Re	Im	
$(\bar{s}_L \gamma^\mu d_L)^2$	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	$\Delta m_D;\ \lvert q/p\rvert,\ \phi_D$
$(\bar{b}_L \gamma^\mu d_L)^2$	5.1×10^2	9.3×10^2	$\Delta m_{B_d};\ S_{\psi K_S}$
$(\bar{b}_R\, d_L)(\bar{b}_L d_R)$	1.9×10^3	3.6×10^3	$\Delta m_{B_d};\ S_{\psi K_S}$
$(\bar{b}_L \gamma^\mu s_L)^2$	1.1×10^2		Δm_{B_s}
$(\bar{b}_R\, s_L)(\bar{b}_L s_R)$	3.7×10^2		Δm_{B_s}

Bounds on the scale of new physics

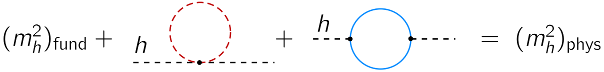
[Isidori et al. 1002.0900]

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



The gauge hierarchy problem

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



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

A new heavy state requires extreme fine-tuning. Two main solutions:

1. Supersymmetry
2. Composite Higgs

New physics at the TeV scale!

The “New Physics flavour problem”

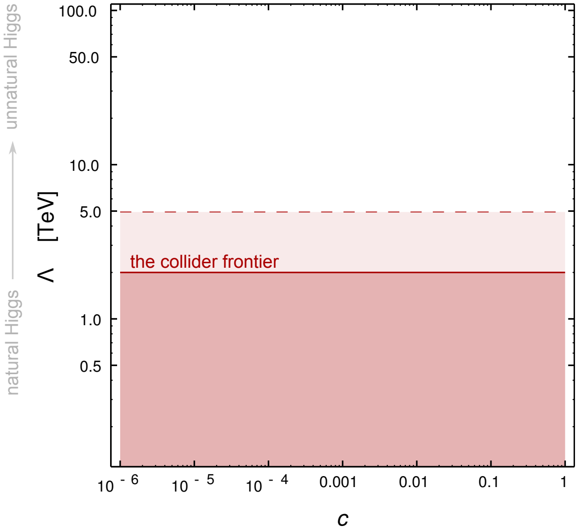
Generic flavour violation and TeV scale NP are incompatible

but

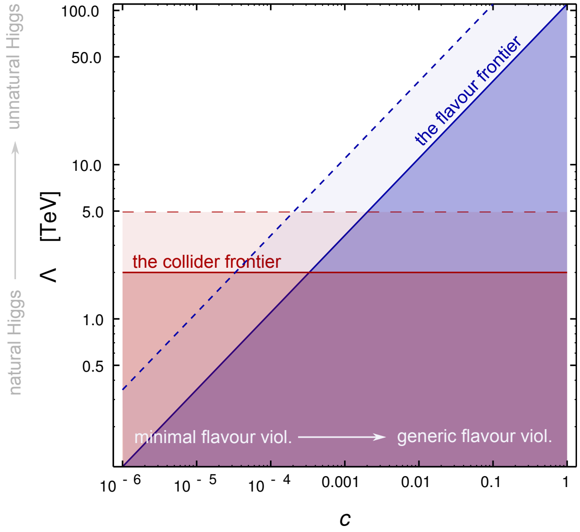
TeV scale NP is required to solve the gauge hierarchy problem

Only way out: NP breaks the flavour symmetry in a highly *non-generic* manner

Collider vs. flavour searches



Collider vs. flavour searches



Implications the flavour problem

TeV scale NP has to be approximately invariant under a flavour symmetry

This flavour symmetry need *not* be

- fundamental
- local
- spontaneously broken
- …

3 examples:

- $U(3)^3$ (Minimal Flavour Violation)
- $U(2)^3$
- $U(1)^9$

$U(3)^3$ (Minimal Flavour Violation)

Assume that the SM Yukawa couplings are the only sources of breaking of the $U(3)_{q_L} \times U(3)_{u_R} \times U(3)_{d_R}$ flavour symmetry *even beyond* the SM. [D'Ambrosio et al. hep-ph/0207036]

- ✓ all FCNCs suppressed by the same CKM elements as in the SM
- ✓ no FCNC operators with new chirality structure (only $\bar{q}_L \gamma^\mu q_L$ as in the SM)
- ✓ testable correlations between down-type FCNCs:

$$A(b \to s) : A(b \to d) : A(s \to d) = (V_{tb} V_{ts}^*)^{1,2} : (V_{tb} V_{td}^*)^{1,2} : (V_{ts} V_{td}^*)^{1,2}$$

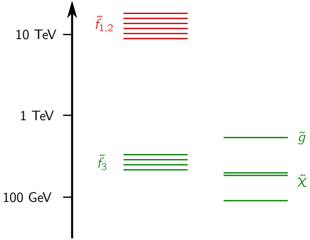
Examples: CMSSM, GMSB

$U(2)^3$

First two generatios transform as doublets, third generation as singlets [Barbieri et al. 1105.2296]

- ✓ Approximately realized in quark masses and mixings ⇒ breaking can be weak
- ✓ same flavour protection as $U(3)^3$ but correlation between K & B broken

Example: a natural SUSY spectrum



$U(2)^3$

First two generatios transform as doublets, third generation as singlets

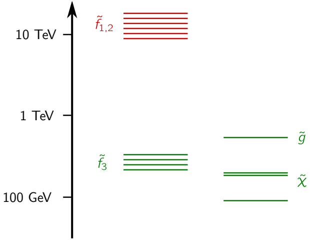
[Barbieri et al. 1105.2296]

- ✓ Approximately realized in quark masses and mixings ⇒ breaking can be weak
- ✓ same flavour protection as $U(3)^3$ but correlation between K & B broken

Example: a natural SUSY spectrum

Other example: MFV with large tan β

[Feldmann and Mannel 0801.1802, Kagan et al. 0903.1794]



$U(1)^9$ (the “chiral hierarchy”)

Breaking the $U(1)$s associated with each quark field by a small amount ϵ ($\epsilon_1 \ll \epsilon_2 \ll \epsilon_3$), one obtains Yukawas of the form

$$Y_{ij} \sim Y_* \epsilon_i \epsilon_j$$

$$V_{ij} \sim \epsilon_i^q / \epsilon_j^q$$

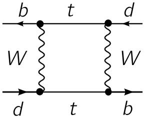
- ✓ CKM-like suppression of FCNCs
- ✓ possible explanation of Yukawa hierarchies (rather than just a parametrization)
- x FCNC operators with new chirality structure (right-handed currents)

Example: Partial compositeness/Randall-Sundrum models

1. **Introduction: the role of flavour**
   - Flavour in the SM: a good parametrization, no explanation
   - Flavour and new physics: an indirect probe of high scales
2. **Hot topics in flavour physics**
   - K, B and B_s mixing
   - Rare B and B_s decays
3. **Outlook**

Meson-antimeson mixing: preliminaries

The weak interaction mixes neutral mesons with their antiparticles:



$$\langle M^0 | \mathcal{H}_{\text{eff}} | \bar{M}^0 \rangle = M_{12} - i\Gamma_{12}$$

$(M = K, B, B_s, D)$

Physical observables

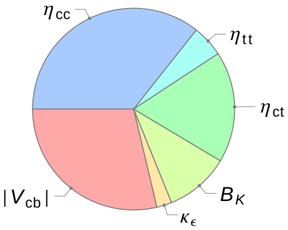
- mixing phase $\phi = \arg(-M_{12}/\Gamma_{12})$
- mass difference $\Delta M \approx 2|M_{12}|$
- width difference $\Delta\Gamma \approx 2|\Gamma_{12}| \cos\phi$

CP violation in K mixing

Recent progress in the SM prediction for $\epsilon_K \propto \text{Im}\, M_{12}^K$:

- estimate of long-distance contributions [Buras et al. 1002.3612]
- NNLO QCD corrections [Brod and Gorbahn 1007.0684, Brod and Gorbahn 1108.2036]

$$|\epsilon_K^{\text{exp}}| = (2.23 \pm 0.01) \times 10^{-3} \qquad |\epsilon_K^{\text{SM}}| = (1.81 \pm 0.28) \times 10^{-3}$$



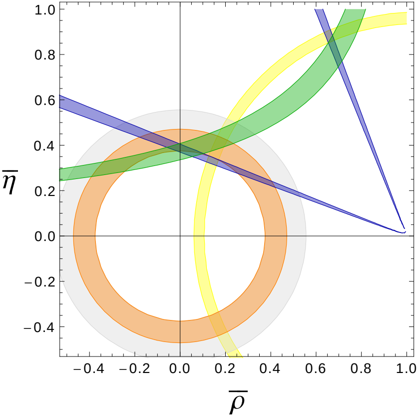
State of the art: [Brod and Gorbahn 1108.2036]

- error due to QCD corrections recently increased due to unexpectedly large NNLO correction. Lattice?
- bag parameter error now subdominant due to effort of lattice community

CP violation in *K* vs. *B* mixing

A closer look at the fit of the CKM “unitarity triangle” reveals some possible tensions among ϵ_K, $\sin(2\beta) = \phi_d$, $\frac{\Delta M_d}{\Delta M_s}$ and $|V_{ub}|$

[Buras and Guadagnoli 0901.2056, . . .]

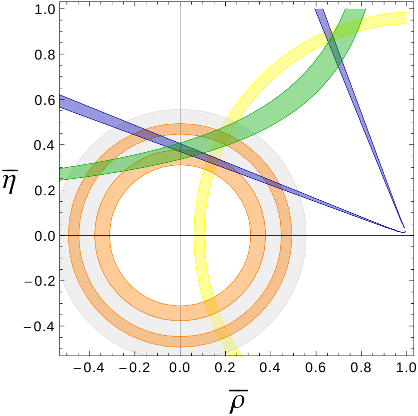


- gray: $|V_{ub}|$ from $B^+ \to \tau^+\nu$

CP violation in *K* vs. *B* mixing

A closer look at the fit of the CKM “unitarity triangle” reveals some possible tensions among ϵ_K, $\sin(2\beta) = \phi_d$, $\frac{\Delta M_d}{\Delta M_s}$ and $|V_{ub}|$

[Buras and Guadagnoli 0901.2056, ...]

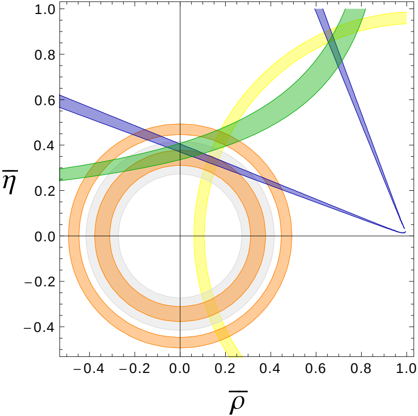


- gray: $|V_{ub}|$ from $B^+ \to \tau^+ \nu$
- $|V_{ub}|$ from inclusive vs. exclusive *B* decays (lattice!)

CP violation in K vs. B mixing

A closer look at the fit of the CKM “unitarity triangle” reveals some possible tensions among ϵ_K, $\sin(2\beta) = \phi_d$, $\frac{\Delta M_d}{\Delta M_s}$ and $|V_{ub}|$

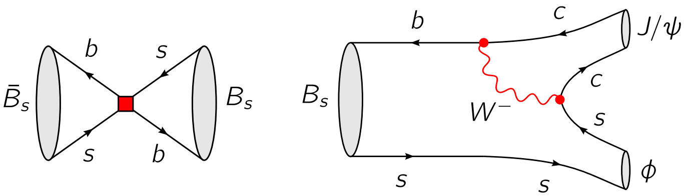
[Buras and Guadagnoli 0901.2056, . . .]



- gray: $|V_{ub}|$ from $B^+ \to \tau^+\nu$
- $|V_{ub}|$ from inclusive vs. exclusive B decays (lattice!)
- New Belle measurement of $\mathrm{BR}(B^+ \to \tau^+\nu)$ [Adachi et al. 1208.4678]

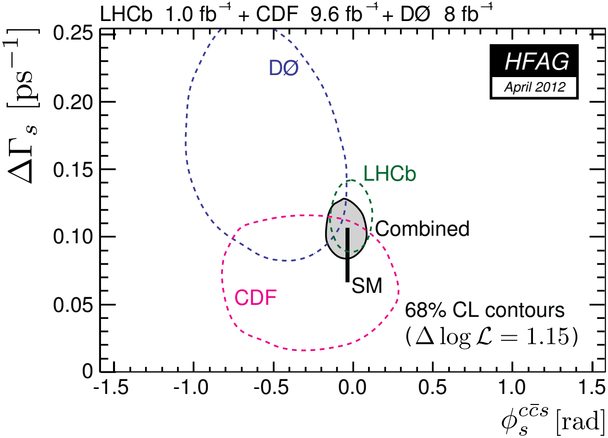
CP violation B_s mixing

The mixing phase ϕ_s can be measured in time-dependent CP asymmetries in $B \to J/\psi K_S$ and $B \to J/\psi \pi\pi$.



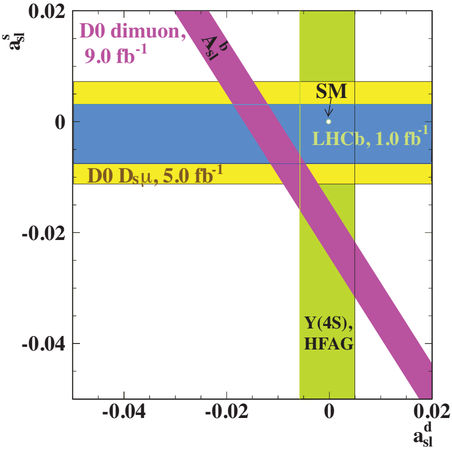
In the SM $\phi_s \approx -2\,\mathrm{Arg}\left(-V_{ts}\right) \approx 2^\circ$ is accidentally small ⇒ sensitive to NP

CP violation B_s mixing: experimental status



No sign of new physics – but $O(100\%)$ modifications of the SM phase still allowed

a_{sl}: another measure of CP violation B_s mixing



$$a_{\rm sl}^q = \frac{\Gamma(B_q \to f) - \Gamma(B_q \to \bar f)}{\Gamma(B_q \to f) + \Gamma(B_q \to \bar f)} = \frac{\Delta\Gamma_q}{\Delta M_q} \tan\phi_q$$

$\Delta F = 2$ implications for flavour symmetries

Typically, new physics effects in

	ϵ_K	ϕ_s	ϕ_d	$\phi_s - \phi_d$
$U(3)^3$	✓	0	0	0
$U(2)^3$	✓	✓	✓	0
$U(1)^9$	✓!	✓	✓	✓

① Introduction: the role of flavour

- Flavour in the SM: a good parametrization, no explanation
- Flavour and new physics: an indirect probe of high scales

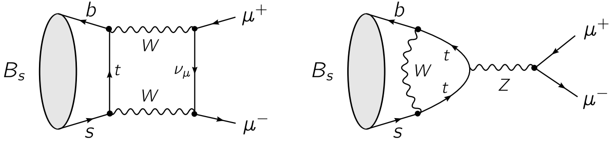
② Hot topics in flavour physics

- K, B and B_s mixing
- Rare B and B_s decays

③ Outlook

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

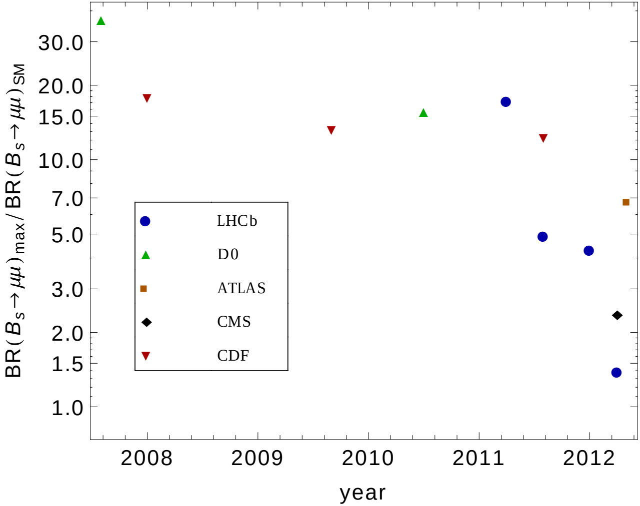
Strongly helicity suppressed in the SM: one of the rarest *B* decays



$$\mathrm{BR}_{\mathrm{SM}} = (3.23 \pm 0.27) \times 10^{-9} \qquad \mathrm{BR}_{\mathrm{exp}} < 4.2 \times 10^{-9}$$

[Buras et al. 1208.0934], [LHCb-CONF-2012-17]

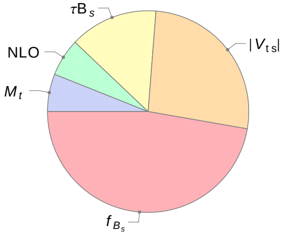
$B_s \to \mu^+\mu^-$: experimental progress



$B_s \to \mu^+\mu^-$: theoretical progress

Dramatic increase in experimental precision ⇒ need to reevaluate TH errors

$$\text{BR}(B_s \to \mu^+\mu^-)_{\text{SM}} \propto \tau_{B_s} f_{B_s}^2 |V_{tb}^* V_{ts}|^2 Y^2(m_t^2/m_W^2) = (3.23 \pm 0.27) \times 10^{-9}$$



State of the art: [Buras et al. 1208.0934]

- Using $f_{B_s} = (227 \pm 8)$ MeV. Much smaller error obtained by HPQCD. Independent confirmation?
- Missing NLO corrections estimated by analogy to $K \to \pi\nu\bar{\nu}$, but might be larger. Full NLO calculation desirable.

$B_s \to \mu^+\mu^-$: theoretical progress

To relate the theoretical BR to experiment, two correction factors have to be taken into account (by the experimentalists)

- Emission of soft photons, depending on the experimental cut on E_γ: $O(-10\%)$ shift [Buras et al. 1208.0934]
- $\Delta\Gamma_s \neq$ leads to difference between flavour-averaged *time-integrated* rate and the unmixed one ($t = 0$): $O(+10\%)$ shift [De Bruyn et al. 1204.1735]

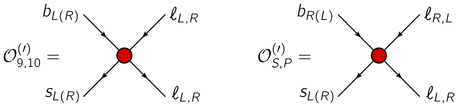
$B_q \to \mu^+\mu^-$ beyond the SM

$U(3)^3$ and $U(2)^3$ predict:

$$\frac{\mathrm{BR}(B_s \to \mu^+\mu^-)}{\mathrm{BR}(B_d \to \mu^+\mu^-)} = \frac{\tau_{B_s} f_{B_s}^2 m_{B_s} |V_{ts}|^2}{\tau_{B_d} f_{B_d}^2 m_{B_d} |V_{td}|^2}$$

An important test, if deviations from the SM are observed

$B_s \to \mu^+\mu^-$ beyond the SM



Two types of contributions: (pseudo)vector and (pseudo)scalar

$$\mathcal{H}_{\text{eff}} \propto -\sum_i C_i\mathcal{O}_i + C_i\mathcal{O}_i'$$

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

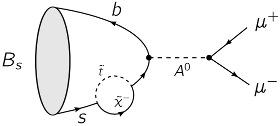
$$S = \frac{m_{B_s}^2}{2}(C_S - C_S') \qquad P = \frac{m_{B_s}^2}{2}(C_P - C_P') + m_\mu(C_{10} - C_{10}')$$

Only C_{10} non-zero in the SM!

$B_s \to \mu^+\mu^-$: scalar contributions

Not helicity-suppressed ⇒ potentially *huge* compared to SM

Prime example: MSSM with large tan β

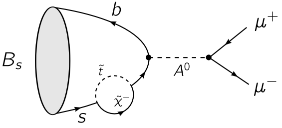


$\propto \frac{m_{B_s}^2}{m_A^2} \tan\beta^6$

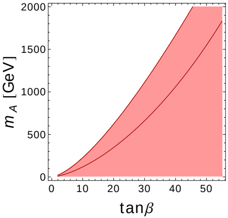
$B_s \to \mu^+\mu^-$: scalar contributions

Not helicity-suppressed ⇒ potentially *huge* compared to SM

Prime example: MSSM with large tan β



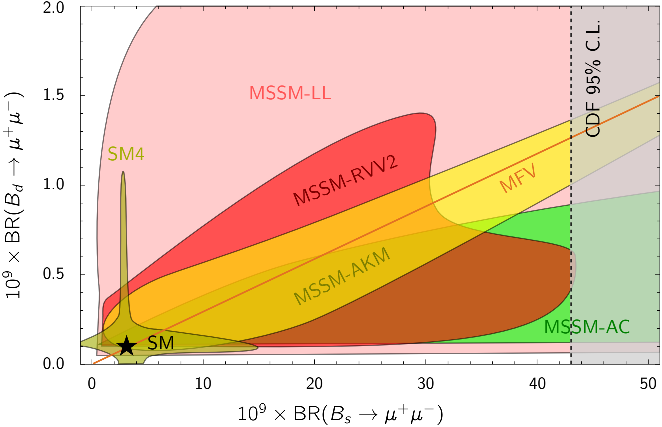
$$\propto \frac{m_{B_s}^2}{m_A^2} \tan\beta^6$$



(assuming $\mu \sim m_{\tilde{t}}$, $A_t = \pm 2 m_{\tilde{t}}$)

$B_s \to \mu^+\mu^-$: scalar contributions

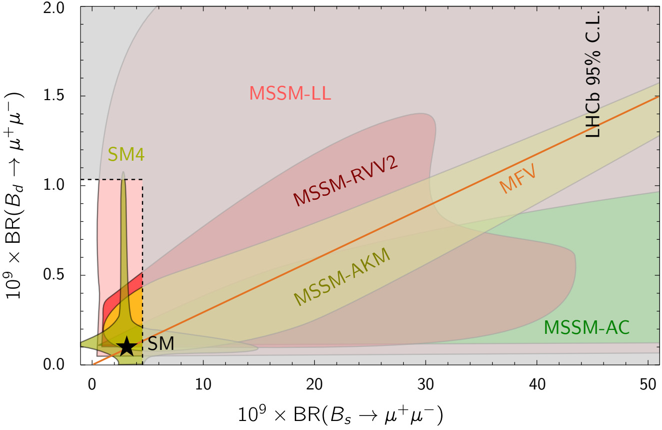
Predictions of some SUSY and non-SUSY models [Straub 1012.3893]



Situation 2 years ago

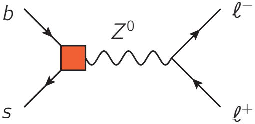
$B_s \to \mu^+\mu^-$: scalar contributions

Predictions of some SUSY and non-SUSY models [Straub 1012.3893]



2012: large scalar contributions are ruled out

$B_s \to \mu^+\mu^-$ is not getting less interesting

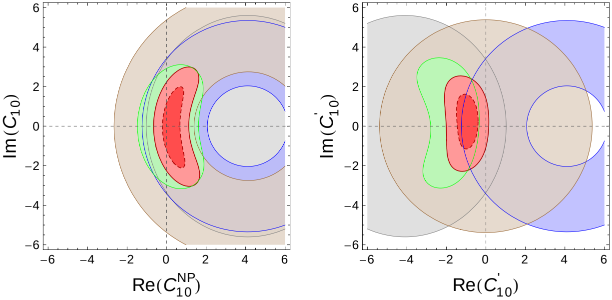


- Many NP models predict effects only in the SM Wilson coefficient C_{10} and/or its chirality-flipped counterpart C_{10}'
- $B_s \to \mu^+\mu^-$ probes $C_{10}^{(\prime)}$ without contamination from other operators like photon penguins
- $B_s \to \mu^+\mu^-$ is only now getting competitive with $b \to s\ell^+\ell^-$ decays probing $C_{10}^{(\prime)}$

$B_s \to \mu^+\mu^-$: contributions to $C_{10}^{(\prime)}$

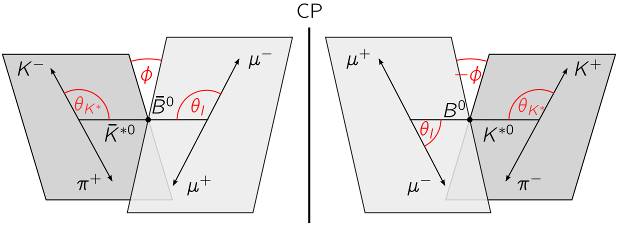
Global constraints on $C_{10}^{(\prime)}$ from $B \to (K, K^*, X_s)\mu\mu$ and $B_s \to \mu\mu$

[Altmannshofer and Straub 1206.0273]



$B_s \to \mu^+\mu^-$ just *started* to enter the interesting region in many NP models

$B \to K^* \mu^+ \mu^-$: a gold mine for new physics searches



- Angular distribution gives access to many observables

$$\frac{d^4\Gamma}{dq^2\, d\cos\theta_l\, d\cos\theta_{K^*}\, d\phi} = \sum_{i,a} \underbrace{I_i^{(a)}(q^2)}_{\text{angular coefficient}} \underbrace{f(\theta_l, \theta_{K^*}, \phi)}_{\text{dependence on angles}}$$

- Self-tagging decay: straightforward to extract CP asymmetries

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

Separate CP-violating and -conserving effects, normalize to reduce form factor uncertainties

CP asymmetries

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

CP-averaged angular coefficients

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

$B \to K^* \mu^+ \mu^-$ observables: status

Measured by LHCb (also Belle, BaBar, CDF)

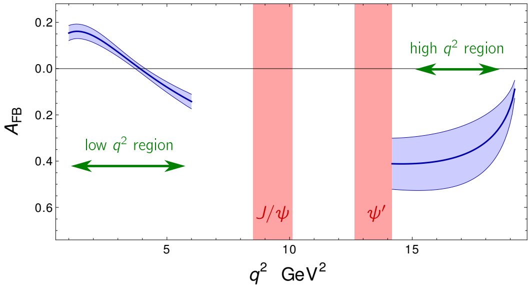
$$\text{BR}, S_6^s (\propto A_{\text{FB}}), S_2^c (\propto F_L), S_3$$

Not measured (or with poor precision), but sensitive to NP

$$S_4\,, S_5\,, A_7\,, A_8\,, A_9$$

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

Different theoretical tools required in the two kinematical limits.

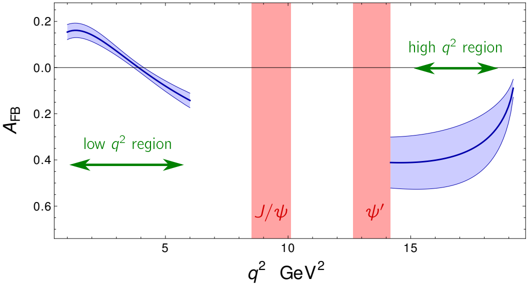


Low q^2

- Non-factorizable corrections not proportional to form factors can be calculated by means of QCD factorization [Beneke et al. hep-ph/0106067, . . .]
- Form factors can be calculated by means of QCD sum rules on the light cone [Ball and Zwicky hep-ph/0412079]

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

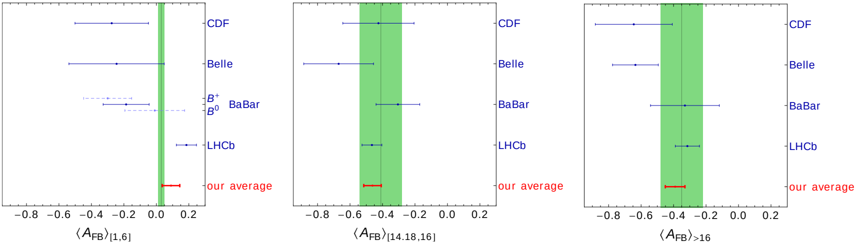
Different theoretical tools required in the two kinematical limits.



High q^2

- Non-perturbative corrections beyond form factors are negligible [Beylich et al. 1101.5118]
- Form factors are poorly known. Lattice!

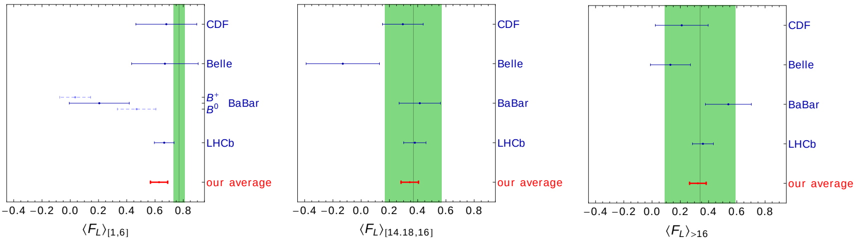
$B \to K^* \mu^+ \mu^-$: theory vs. experiment



Everything consistent with the SM up to now. At high q^2, theory precision already saturated…

[Altmannshofer and Straub 1206.0273]

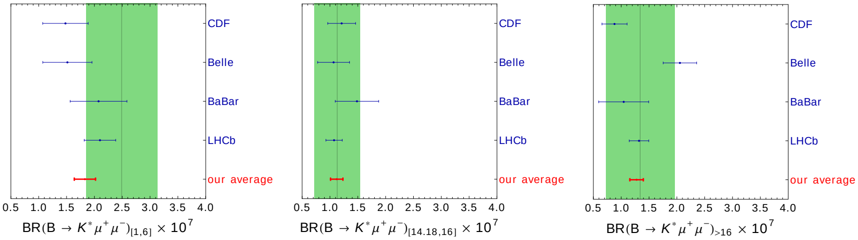
$B \to K^* \mu^+ \mu^-$: theory vs. experiment



Everything consistent with the SM up to now. At high q^2, theory precision already saturated…

[Altmannshofer and Straub 1206.0273]

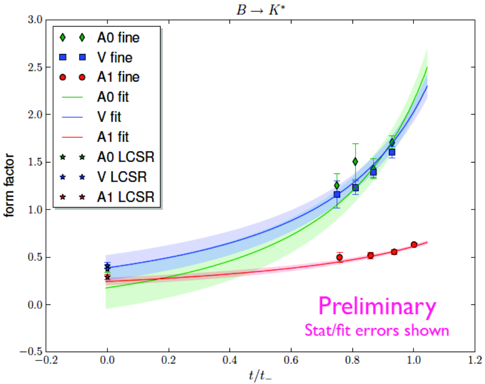
$B \to K^* \mu^+ \mu^-$: theory vs. experiment



Everything consistent with the SM up to now. At high q^2, theory precision already saturated…

[Altmannshofer and Straub 1206.0273]

$B \longrightarrow K^*$ form factors: lattice progress

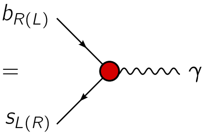


[M. Wingate at the Workshop on rare and exclusive *B* decays, Sussex, November 2012], see also [Liu et al. 1101.2726]

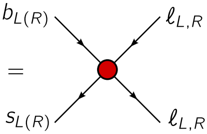
$B \to K^*\mu^+\mu^-$ Wilson coefficients

$$\mathcal{H}_{\text{eff}} \propto -\sum_i C_i \mathcal{O}_i + C_i' \mathcal{O}_i'$$

$$\mathcal{O}_7^{(\prime)} =$$

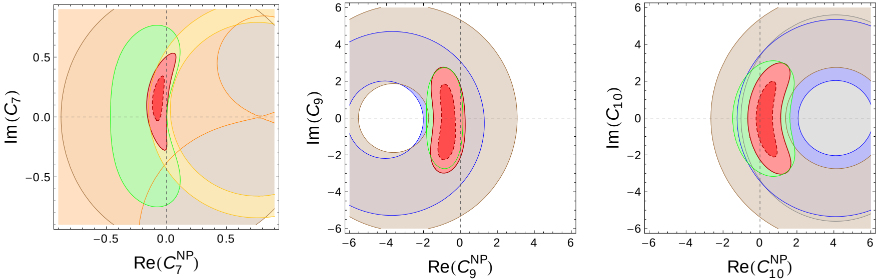


$$\mathcal{O}_{9,10}^{(\prime)} =$$



$B \to K^*\mu^+\mu^-$ probes a host of Wilson coefficients sensitive to NP

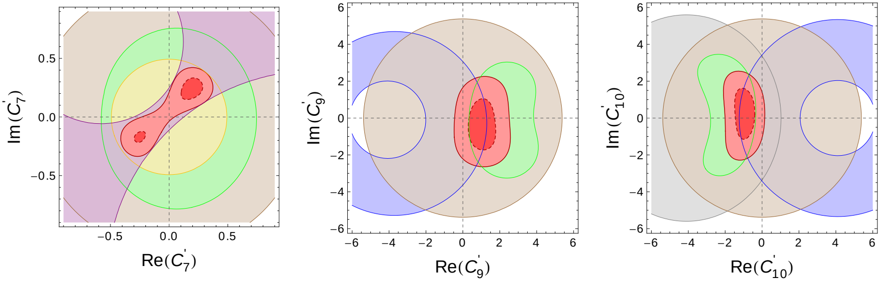
Global contraints on Wilson coefficients



Constraints from $B \to X_s\gamma$, $B \to (K, K^*, X_s)\mu\mu$ and $B_s \to \mu\mu$

[Altmannshofer and Straub 1206.0273]

Global contraints on Wilson coefficients



Constraints from $B \to X_s\gamma$, $B \to (K, K^*, X_s)\mu\mu$ and $B_s \to \mu\mu$

[Altmannshofer and Straub 1206.0273]

$\Delta F = 1$ implications for flavour symmetries

Typically, new physics effects in

	$\text{Re}\, C_7$	$\text{Im}\, C_7$	$\text{Re}\, C_{9,10}$	$\text{Im}\, C_{9,10}$	$C'_{7,9,10}$
$U(3)^3$	✓	✓	✓	0	0
$U(2)^3$	✓	✓	✓	✓	0
$U(1)^9$	✓	✓	✓	✓	✓

① Introduction: the role of flavour

- Flavour in the SM: a good parametrization, no explanation
- Flavour and new physics: an indirect probe of high scales

② Hot topics in flavour physics

- K, B and B_s mixing
- Rare B and B_s decays

③ Outlook

Experimental outlook

An incomplete list of promising observables at LHC . . .

- $B_{s,d} \to \mu^+\mu^-$
- $B \to K^*\mu^+\mu^-$, including CP asymmetries
- ϕ_s
- D decays, D-$\bar{D}$ mixing

Experimental outlook

An incomplete list of promising observables at LHC . . .

- $B_{s,d} \to \mu^+\mu^-$
- $B \to K^*\mu^+\mu^-$, including CP asymmetries
- ϕ_s
- D decays, D-$\bar{D}$ mixing

. . . and beyond (SuperB, Belle-II, NA62, KOTO, MEG, . . .)

- $K^+ \to \pi^+\nu\bar{\nu}$, $K_L \to \pi^0\nu\bar{\nu}$
- $B \to K\nu\bar{\nu}$
- $B \to \tau\nu$, $B \to D^{(*)}\tau\nu$
- lepton flavour violation ($\mu \to e\gamma$, . . .)

. . . and of course precision measurements of the CKM elements/angles

Conclusions I

- The SM description of flavour is successful but the origin of the flavour structure must lie beyond
- If there is TeV scale new physics, there must be a weakly broken flavour symmetry
- Flavour and collider searches are complementary
- No significant deviations from the SM yet, but still many opportunities

Conclusions II

There were no low-hanging fruits . . .

Conclusions II

Photo: The.Rohit (flickr)

. . . but there's plenty of room at the top.