Flavour physics

M. Beneke (TU München)

Latsis Symposium “Nature at the Energy Frontier”
Zürich, June 3-6, 2013

Outline

• Introduction
• Unitarity triangle
• \( B_s \) (mixing, \( B_s \to \mu^+ \mu^- \), non-leptonic)
• Electroweak penguin decays
• Flavour-violating Higgs couplings
• Loops and flavour violation in RS
Flavour and CP violation in the SM

\[ SU(3) \times SU(2) \times U(1)_Y \]

Field content and gauge charges

\[
- y^d_i (\bar{Q}'_L V^\dagger_{CKM})_i \Phi d_Ri - y^u_i \bar{Q}'_L \tilde{\Phi} u_Ri \\
- y^e_i \bar{L}_i \Phi e_Ri + h.c.
\]

Only charged current.
No Higgs FCNC ⇒ little direct impact of Higgs discovery on SM flavour physics.

\[
- \frac{f_{ij}}{\Lambda} [ (\bar{L}^T \epsilon)_i i \sigma^2 \Phi ] [ \Phi^T i \sigma^2 L^*_j ] + h.c.
\]

\[
\sin \theta_{13} \text{ measured} \Rightarrow \text{CPV measurements in neutrino sector possible.}
\]

FV in the SM is natural and predictive (especially CPV) ...
Flavour and CP violation in the SM

\[ SU(3) \times SU(2) \times U(1)_Y \]

Field content and gauge charges

\[-y_i^d(\bar{Q}_L^i V_{\text{CKM}}^\dagger)\Phi d_R i - y_i^u \bar{Q}_L^i \tilde{\Phi} u_R i
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\[-y_i^l \bar{L}_i \Phi e_R i + \text{h.c.} \]

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\( \sin \theta_{13} \) measured \( \Rightarrow \) CPV measurements in neutrino sector possible.

FV in the SM is natural and predictive (especially CPV) ...

- What is \( y^u,d_i, V_{\text{CKM}} \)? Is \( V_{\text{CKM}} \) complex? Why is \( y^u,d_i, V_{\text{CKM}} \) what it is? (Origin of flavour hierarchies)

- Is this all there is? If not, what is it? Why didn’t we see it already? (The other flavour problem)

The gauge hierarchy-flavour problem

SM presumably valid only below some scale $\Lambda$

$$\mathcal{L}_{\text{SM}} = \mathcal{L}_{\text{dim}4} - \frac{\Lambda^2}{2} \Phi \Phi + \sum_i \frac{1}{\Lambda^2} (\bar{q}q\bar{q}q)_i + \ldots$$

- Scalar mass term is the only dimensionful parameter in the renormalizable part of the Lagrangian.
  - Sets the electroweak scale.
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- Scalar mass term receives large quantum corrections if there is another scale $\Lambda$. Electroweak physics requires $\Lambda \leq M_W/g \approx \text{few hundred GeV}$.

- But flavour physics restricts the scale of dimension-6 operators to

  $$\Lambda \geq 10^{4-5} \text{ TeV} \quad (\bar{s}d)(\bar{s}d) \quad \Lambda \geq 10^3 \text{ TeV} \quad (\bar{b}d)(\bar{b}d)$$

  unless it is special (weak coupling, loop suppression, CKM-like suppressions).
  Generic scale far beyond reach of LHC!
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Difficult to construct natural models.
But the argument may simply be wrong because nature may not care about naturalness ...
Flavour in the LHC Era

LHCb (indirect)
- $B_s$ physics
- Electroweak penguins
- $\gamma$ from $B \to D K$s
- Charm

LHC (“high-$p_T$”)
- Higgs flavour
- top flavour
- Direct production
Flavour in the LHC Era

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Interplay?
Flavour in the LHC Era

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Interplay?

LHC (“high-$p_T$”)
- Higgs flavour
- top flavour
- Direct production

BSM only. Specific models
The Unitarity Triangle

1995 (top discovery)

2001 (B factory turn-on)

2013 (Precision flavour physics)

• Anomalies disappeared ($B \to \tau \nu$) or became implausible (Di-muon asymmetry $A_{SL}$).

• Never before as consistent and precise • MFV paradigm

• UT triangle fit no longer an adequate representation of all tests of the SM flavour sector.

Non-standard flavour physics can still be hidden.

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**$|V_{ub}|$ problem**

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Kinematic constraints due to charm background.
HQE + resummation.

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Lattice QCD
QCD sum rules
analyticity
Inclusive $B \rightarrow X_u \ell \nu$

$|V_{ub}| = (4.41 \pm 0.15_{\text{exp}}^{+0.15}_{-0.17_{\text{th}}}) \cdot 10^{-3}$

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Lattice QCD
QCD sum rules
analyticity

- $V_{ub} - \sin 2\beta - \epsilon_K$ connection
- Bet on exclusive ...
- Some two-loop results for inclusive (fully differential (Brucherseifer, Caola, Melnikov, 2012); hard coefficient for resummation (Bonciani, Ferroglia; Asavian, Greub, Pecjak; MB, Huber, Li; Bell, 2008)) not yet implemented.

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$B_s$ lifetime difference and mixing phase

$$i \frac{d}{dt} \left( \frac{|B_s(t)\rangle}{|\bar{B}_s(t)\rangle} \right) = \left( M_s^s - \frac{i}{2} \Gamma_s^s \right) \left( \frac{|B_s(t)\rangle}{|\bar{B}_s(t)\rangle} \right)$$

Three observables related to mixing:

- $\Delta m_s / \Gamma_s$ large $\rightarrow$ many oscillations per lifetime
  $$M_{12} \propto (V_{ts}^* V_{tb})^2$$

- $\Delta \Gamma_s (|\Gamma_{12}^s|)$ relevant. Significant fraction of common final states from $b \rightarrow c\bar{c}s$.
  $$\frac{\Delta \Gamma}{\Gamma} = (1, \alpha_s) \times 16\pi^2 \frac{\Lambda^3}{m_b^3} + 16\pi^2 \frac{\Lambda^4}{m_b^4} + \ldots \implies \Delta \Gamma_s = (0.090 \pm 0.018) \text{ ps}^{-1}$$
  [Lenz-Nierste update, 1102.4274]

OPE+HQE [MB, Buchalla, Dunietz, 1996; MB et al., 1998] + Lattice

- Phase [MB et al, 1998, 2003; Ciuchini et al., 2003]
  $$\phi_s = \arg \left( -\frac{M_{12}^s}{\Gamma_{12}^s} \right) = 0.22^\circ \pm 0.06^\circ$$
  $$2\beta_s = 2\arg \left( -V_{tb}^* V_{ts} / (V_{cb}^* V_{cs}) \right) = 2.1^\circ \pm 0.1^\circ$$
\( \Delta \Gamma_s \) and \( \beta_s \) from \( B_s \to J/\psi \phi \) and related

- Last loophole for large NP in \( B_{d,s} \) mixing closed
- HQE and Quark-Hadron Duality works in \( b \to c\bar{c}s \).
- No effect large expected in MFV models.
- Generic models would affect \( B_d \) mixing more than \( B_s \) due to stronger CKM suppression. But quark flavour mixing may be related to lepton neutrino mixing.
- To complete the picture

\[
a_{sl} = \frac{\Gamma(\bar{B}_s \to \ell^+X) - \Gamma(B_s \to \ell^-X)}{\Gamma(\bar{B}_s \to \ell^+X) + \Gamma(B_s \to \ell^-X)} = \frac{\Delta \Gamma_s}{\Delta M_s} \tan \Phi_s
\]

Anomaly in D0 measurement.
\[ B_s \rightarrow \mu^+ \mu^- \]

\[
\text{Br}(B_s \rightarrow \mu^+ \mu^-) = \frac{G_F^2 \alpha^2}{64 \pi^3 f_{B_s}^2 \tau_{B_s} m_{B_s}^3} |V_{tb} V_{ts}^*|^2 \sqrt{1 - \frac{4m_{\mu}^2}{m_{B_s}^2}} \times \left\{ \left(1 - \frac{4m_{\mu}^2}{m_{B_s}^2}\right) |C_S - C'_S|^2 + |(C_P - C'_P) + \frac{2m_{\mu}}{m_{B_s}} (C_{10} - C'_{10})|^2 \right\}
\]

- SM only \( C_{10} \Rightarrow \) helicity suppression
- Sensitive to scalar couplings.
\[ B_s \rightarrow \mu^+ \mu^- \]

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- **SM only** $C_{10} \Rightarrow$ helicity suppression
  Sensitive to scalar couplings.

- **Width difference correction** [De Bruyn et al., 2012]

\[
\langle \Gamma(B_s(t) \rightarrow f) \rangle \equiv \Gamma(B_s(t) \rightarrow f) + \Gamma(\bar{B}_s(t) \rightarrow f) = R^f_H e^{-\Gamma^s_{H+t}} + R^f_L e^{-\Gamma^s_{L+t}}
\]

\[
\text{BR}(B_s \rightarrow f)_{\text{obs}} = \frac{1}{2} \int_0^\infty dt \langle \Gamma(B_s(t) \rightarrow f) \rangle = \frac{\tau_{B_s}}{2} (R^f_H + R^f_L) \left[ \frac{1 + A^f_{\Delta \Gamma} y_s}{1 - y_s^2} \right]
\]

\[ y_s = \frac{\Delta \Gamma_s}{2 \Gamma_s} \approx 0.1 \]
\[ B_s \rightarrow \mu^+ \mu^- \]

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\text{Br}(B_s \rightarrow \mu^+ \mu^-) = \frac{G_F^2 \alpha^2}{64 \pi^3 f_{B_s}^2 \tau_{B_s} m_{B_s}^3} |V_{tb} V_{ts}^*|^2 1 - \frac{4 m_{\mu}^2}{m_{B_s}^2} \sqrt{1 - 4 m_{\mu}^2 m_{B_s}^2} \times \left\{ \left( 1 - \frac{4 m_{\mu}^2}{m_{B_s}^2} \right) |C_S - C'_S|^2 + |(C_P - C'_P) + \frac{2 m_{\mu}}{m_{B_s}} (C_{10} - C'_{10})|^2 \right\}
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\]

\[ y_s = \Delta \Gamma_s / (2 \Gamma_s) \approx 0.1 \]

- LHCb [1211.2674]: \((3.2^{+1.5}_{-1.2}) \times 10^{-9}\) vs. Theory [Buras et al., 1208.0934]: \((3.54 \pm 0.30) \times 10^{-9}\)
$B_s \rightarrow \mu^+ \mu^-$ model killing

[Straub, 1205.6094]
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Scalar FCNC cannot play an important role in non-helicity-suppressed amplitudes.

Suppression relative to SM possible for pseudoscalar Higgs interfering with SM axial-vector contribution.

[Altmannshofer, 1306.0022]
$B_s \rightarrow \mu^+ \mu^-$ model killing

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- Suppression relative to SM possible for pseudoscalar Higgs interfering with SM axial-vector contribution.
Hadronic matrix elements

| None – pure quantum interference | $\langle 0 | \mathcal{O} | B \rangle$ |
|----------------------------------|--------------------------------------|
|                                  | $\langle B | \mathcal{O} | B \rangle$ |
|                                  | $\langle M | \mathcal{O} | B \rangle$ |
| HQE/OPE, lattice, (QCD sum rules) |                                      |
| QCD factorization, (flavour symmetries) | $\langle M_1 M_2 | \mathcal{O} | B \rangle$ |

Increasingly difficult
**Hadronic matrix elements**

None – pure quantum interference

\[ \langle 0 | \mathcal{O} | B \rangle \quad \langle B | \mathcal{O} | B \rangle \quad \langle M | \mathcal{O} | B \rangle \quad \langle M_1 M_2 | \mathcal{O} | B \rangle \]

HQE/OPE, lattice, (QCD sum rules)

QCD factorization, (flavour symmetries)

Increasingly difficult

\( \gamma \) from \( B \to DK \) [and related methods]

\( 2\beta_{B_s} \)

\( B \to \tau \nu \tau \)

\( B_s \to \mu^+ \mu^- \)

\( |V_{ub}| \)

\( B \to D \tau \nu \tau \)

\( \Delta M_{B_d,B_s} \)

\( \Delta \Gamma_{B_s} \)

\( B \to K \nu \bar{\nu} \)

\( B \to \rho \gamma \)

Direct CP asym

\( B_s \to \pi K, KK, \ldots \)

\( B_s \to \pi \pi \)

\( B_s \to \phi \phi, K^{*0} \bar{K}^{*0} \)

Many new LHCb results
Hadronic matrix elements from QCD factorization
[BBNS, 1999-2003]

Heavy quark limit: $m_b \gg \Lambda_{QCD}$
Large-energy limit: $E_M \approx m_b/2 \gg \Lambda_{QCD}$
Scales: $m_b, \sqrt{m_b\Lambda_{QCD}}, \Lambda_{QCD}, (M_{EW}, \Lambda_{NP})$

- Reduces $\langle M_1 M_2 | O | B \rangle$ to simpler $\langle M | O | B \rangle$ (form factors), $\langle 0 | O | B \rangle$, $\langle 0 | O | M \rangle$ (decay constants and distribution amplitudes).
- Calculation from first principles, but limited accuracy by $\Lambda_{QCD}/m_b$ corrections.
Status of NNLO radiative calculations

\[ \langle M_1 M_2 | C_i O_i | \bar{B} \rangle \mathcal{L}_{\text{eff}} = \sum_{\text{terms}} C(\mu_h) \times \left\{ F_{B \rightarrow M_1} \times \left( T^I(\mu_h, \mu_s) \right) \right. \]
\[ \left. 1 + \alpha_s + \ldots \right\} \]
\[ + f_B \Phi_B(\mu_s) \times \left( J^{\Pi}(\mu_h, \mu_I) \right) \]
\[ + \frac{1}{m_b} \text{-suppressed terms} \]

Tree-dominated decays complete at NNLO.
Other non-leptonic and \( B \rightarrow (M, \gamma)(\gamma, \ell^+ \ell^-) \) at NLO (= partly 2-loop).
No NNLO result yet on direct CP asymmetries: \( A_{\text{CP}} = [c \times \alpha_s]_{\text{NLO}} + \mathcal{O}(\alpha_s^2, \Lambda/m_b) \)
Electroweak penguin decay $B \to K^* (\to K\pi) \ell^+ \ell^-$ [and related]

- Sensitive to TeV scale new particles in a cleaner environment than purely hadronic processes.

$$O_7^{(i)} = -\frac{g_{em}\hat{m}_b}{8\pi^2} \bar{s}\sigma^{\mu\nu}(1\pm\gamma_5)bF_{\mu\nu}$$

$$O_9^{(i)} = \frac{\alpha_{em}}{2\pi} (\bar{\ell}\ell)_V,A (\bar{s}b)_{V\pm A}$$

$$O_{S,P,T}$$
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\]

\[
\mathcal{O}_{9,10}^{(i)} = \frac{\alpha_{\text{em}}}{2\pi} (\bar{\ell}\ell)_{V,A} (\bar{s}b)_{V \pm A}
\]

\[
\mathcal{O}_{S,P,T}
\]

- Powerful diagnostic due to access to different tensor structures and chiralities through kinematic distributions and asymmetries

\[
\frac{d^4\Gamma}{dq^2 d\cos \theta_l d\cos \theta_K d\phi} = \frac{9}{32\pi} J(q^2, \theta_l, \theta_K, \phi)
\]

12 (10,8) angular coefficients $I_i(q^2) + \text{CP conjugates}$. 

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Theory description

- $B \rightarrow K^*$ form factors not enough. Charm loops introduce a “hadronic component” of the virtual photon, as well as resonances.
- Amplitude has two components

$$\langle K^* \ell \ell | H_{\text{eff}} | B \rangle = \sum_i a_i (C_7^{(r)}, 9, 10, \ldots) F^{B \rightarrow K^*}_i + \frac{ie^2}{q^2} \langle \ell \ell | \bar{l} \gamma \mu l | 0 \rangle \int d^4 x \ e^{iq \cdot x} \langle K^* | T(j_{\text{em}}^\mu(x) H_{\text{had}}(0)|B \rangle$$

**Electroweak penguins:**
- local
- sensitive to new physics

**QCD:**
- non-local
- NP constrained by non-leptonics:
  - photon pole, charmonium resonances

[Diagrams showing quark and form factor interactions]
Lepton invariant mass spectrum and theoretical approaches


$$\langle \ell \ell K^* | O_i | \bar{B} \rangle = C_i \xi + \Phi_B \otimes T_i \otimes \Phi_{K^*} + \mathcal{O}(\Lambda/m_b)$$

- QCD factorization

OPE/HQE for $q^2 \geq 15 \text{ GeV}^2$ [Grinstein, Pirjol, 2004; Beylich et al., 2011]

$$\langle \ell \ell K^* | O_i | \bar{B} \rangle = C_i F_{B \rightarrow K^*} + \mathcal{O}(\Lambda^2/m_b^2)$$

Power corrections and duality violation (integrated) estimated below 2%.

- Charmonium resonance region e.g. [Khodjamirian et al., 2010, 2012]. No quark-hadron duality in this region [MB, Buchalla, Neubert, Sachrajda, 2009].

![Graph showing differential branching fraction as a function of $s = q^2/m_b^2$](image)

**Fig. 2** Differential $B \rightarrow X_{s,t}^{+} l^- \bar{l}^-$ branching fraction as a function of $s = q^2/m_b^2$ including the effect of charm resonances in.
Lepton invariant mass spectrum and theoretical approaches

- QCD factorization for \( q^2 \leq 6 \text{ GeV}^2 \) [MB, Feldmann, Seidel, 2001; 2004]

\[
\langle \ell \ell K^* | O_i | \bar{B} \rangle = C_i \xi + \phi_B \otimes T_i \otimes \Phi_{K^*} + \mathcal{O}(\Lambda/m_b)
\]

- OPE and HQE for \( q^2 \geq 15 \text{ GeV}^2 \) [Grinstein, Pirjol, 2004; Beylich et al., 2011]

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**Fig. 2** Differential $B \rightarrow X_s \ell^+\ell^-$ branching fraction as a function of $s = q^2/m_b^2 \equiv m_{X_s}^2/m_b^2$, including the effect of charm resonances in

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Form factors and “effective Wilson coefficients”

- Key point at large recoil: only two independent form factors due to helicity and parity conservation of the strong interaction – up to calculable $\alpha_s$ corrections [Charles et al., 1998, MB, Feldmann, 2000], e.g.,

$$\langle K^*(\lambda = \pm 1)|\bar{s}p_{R/L}\Gamma b|\bar{B}\rangle \Rightarrow \xi_\perp(q^2)$$
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- Double differential distribution with “effective Wilson coefficients”

$$\frac{d^2\Gamma}{dq^2 d\cos \theta} = \frac{G_F^2 |V_{ts}^* V_{tb}|^2}{128\pi^3} M_B^3 \lambda(q^2, m_{K^*}^2)^3 \left(\frac{\alpha_{\text{em}}}{4\pi}\right)^2 \times \left[ (1 + \cos^2 \theta) \frac{2q^2}{M_B^2} \xi_{\perp}(q^2)^2 \left( |C_9, \perp(q^2)|^2 + C_{10}^2 \right) \\
+ (1 - \cos^2 \theta) \left( \frac{E \xi_{||}(q^2)}{m_{K^*}} \right)^2 \left( |C_9, ||(q^2)|^2 + C_{10}^2 \Delta_{||}(q^2)^2 \right) - \cos \theta \frac{8q^2}{M_B^2} \xi_{\perp}(q^2)^2 \text{Re}(C_9, \perp(q^2)) C_{10} \right]$$
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\right.
$$

$$\left. + (1 - \cos^2 \theta) \left(\frac{E \xi_\parallel(q^2)}{m_{K^*}}\right)^2 \left(|C_9, \parallel(q^2)|^2 + C_{10}^2 \Delta_\parallel(q^2)^2\right) - \cos \theta \frac{8q^2}{M_B^2} \xi_\perp(q^2)^2 \Re(C_9, \perp(q^2)) C_{10}\right]$$

$$C_{9, \perp(q^2)} \equiv C_9 + \frac{2m_b M_B}{q^2} \frac{T_\perp(q^2)}{\xi_\perp(q^2)} = C_9 + Y(q^2) + \frac{2m_b M_B}{q^2} C_{\text{eff}}^7 + \ldots$$

$$C_{9, \parallel(q^2)} \equiv C_9 - \frac{2m_b}{M_B} \frac{T_\parallel(q^2)}{\xi_\parallel(q^2)} = C_9 + Y(q^2) + \frac{2m_b}{M_B} C_{\text{eff}}^7 - e_q \frac{4M_B}{m_b} (\bar{C}_3 + 3\bar{C}_4)$$

$$\times \frac{\pi^2}{N_c} \frac{f_{B(K^*)}}{M_B(E/m_{K^*})\xi_\parallel(q^2)} \int d\omega \frac{M_B \Phi_{B, -(\omega)}}{M_B \omega - q^2 - i\epsilon} + \ldots$$

$$T_a = \xi_a \left(C_a^{(0)} + \frac{\alpha_s C_F}{4\pi} C_a^{(1)}\right) + \frac{\pi^2 f_{B(K^*)}^a}{N_c M_B} \equiv_a \sum_{\pm} \int \frac{d\omega}{\omega} \Phi_{B, \pm(\omega)} \int_0^1 du \Phi_{K^*, a(u)} T_a, \pm(u, \omega)$$
Forward backward asymmetry zero: $\text{Re}(C_9, \perp (q_0^2)) = 0$

- Zero arises if $C_9$ and $C_7$ have different sign.

Almost free from hadronic uncertainties (protected from form factor uncertainty)


$$q_0^2[K^*^0] = 4.36^{+0.33}_{-0.31} \text{ GeV}^2 \quad q_0^2[K^*^+] = 4.15 \pm 0.27 \text{ GeV}^2$$

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\[dA_{FB}/dq^2(\text{GeV}^{-2})\]

\[A_{FB}\]

\[C_9(4.6 \text{ GeV})\]

\[C_9 = -\frac{2M_Bm_B}{q_0^2}C_7^{\text{eff}} \text{Re}Y(q_0^2)+\text{known NLO correction}\]

M. Beneke (TU München), Flavour physics

Latsis Symposium, Zürich, 06 June 2013
Full angular analysis

• $A_{FB}(q^2)$ is protected from form factor uncertainty only at one point. Can do much better, when angular amplitudes $I_i(q^2)$ are measured. [Egede et al. 2008, 2009, 2010; Altmannshofer et al. 2008; Bobeth et al. 2008; Bobeth, Hiller, van Dyk, 2010, 2011; Matias et al., 2012; Beaujean et al., 2012; Descotes-Genon et al., 2012; Jäger, Martin Camalich, 2012]

• Basic idea: Construct (most) $I_i$ such that

$$I_i(q^2) \propto |\xi_\perp(q^2)|^2 \quad \text{or} \quad |\xi_\parallel(q^2)|^2 \quad \text{or} \quad \xi_\perp(q^2)\xi_\parallel(q^2)$$

and take ratios such that form factors cancel. “Theoretically clean” for all $q^2$.

$$P_i(q^2) = a_i(q^2) + \frac{\alpha_s}{\xi_a(q^2)} \times \text{spectator scattering} + O\left(\frac{\Lambda}{m_b}\right)$$

• Example: Transversity amplitude is protected for all $q^2$.

$$A^{(2)}_T(q^2) = \frac{|A_\perp|^2 - |A_\parallel|^2}{|A_\perp|^2 + |A_\parallel|^2}$$
Full angular analysis

Theoretical error including $\Lambda/m_b$ and SUSY scenarios (1 TeV masses)

Experimental sensitivity, 10 fb$^{-1}$ at LHCb.

Experimental sensitivity for SUSY scenario b.

- **Unique flavour laboratory:** The set of all angular observables allows one to determine magnitude, phase and chirality of the magnetic penguin and electroweak penguin coefficients. [Example: $A_T^{(2)}(q^2)$ is negligible in the SM, and proportional to $C_7^{(f)}$ BSM.]

- Starts being measured at LHCb $\Rightarrow$ Egede’s talk

- Primary application of factorization to LHCb physics.
Summary on “traditional” flavour physics

- Only the beginning of flavour physics at LHCb ... SuperKEKB to come (2016)
- $B_s$ mixing, scalar FCNCs, electroweak penguins, charm, ... flavour physics looks more SM-like than ever
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- Don’t forget: $\mathcal{O}(20\%)$ effects often still possible.
  In models with flavour structure and weak coupling flavour physics is only sensitive to the TeV scale.
- Precision matters: “clean” observables and good theoretical methods.
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- **Precision** matters: “clean” observables and good theoretical methods.

- SM could be valid to very high scales ...
“There is a theory in physics that explains, at the deepest level, nearly all of the phenomena that rule our daily lives [...] It surpasses in precision, in universality, in its range of applicability from the very small to the astronomically large, every scientific theory that has ever existed. This theory bears the unassuming name ‘The Standard Model of Elementary Particles’ [...] It deserves to be better known, and it deserves a better name. I call it ‘The Theory of Almost Everything’.”

Two new players on the field

**Top**

- Low-energy phenomenology determined by $V_{ts}, V_{td} \ll 1$: Meson-mixing, down-type quark FCNC
- Collider phenomenology (top decay, single top production) dominated by $V_{tb} \sim 1$.
- FCNC strongly GIM suppressed

\[
\text{Br}(t \to c\gamma) \sim |V_{cb}|^2 \times \frac{\alpha}{16\pi^3} \times \left(\frac{m_b^2}{m_t^2}\right)^2 \sim 10^{-13}
\]

$\Rightarrow$ Little interplay in the SM.
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Top and Higgs flavour physics is BSM physics
Flavour-changing couplings of the Higgs boson

$SU(3) \times SU(2) \times U(1)_Y$ effective Lagrangian [Buchmüller, Wyler, 1985; Grzadkowski et al., 2010]

\[
\mathcal{L} = -\lambda_{ij}L_i \phi e_R - \frac{\lambda'_{ij}L_i \phi e_R}{\Lambda^2} (\phi^\dagger \phi) + \phi^\dagger i \overleftrightarrow{D} \phi (\bar{\psi} \psi) \text{ operators}
\]

+ quark operators

\[
\sqrt{2}m = \lambda + \frac{v^2}{2\Lambda^2} \lambda' \quad \sqrt{2}Y = \lambda + \frac{3v^2}{2\Lambda^2} \lambda'
\]

Breaks mass-coupling relation.
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\]

Breaks mass-coupling relation.

Misalignment generates Higgs FCNC

\[
\mathcal{L}_Y = -Y_{\mu\tau} \bar{\mu}_L \tau_R H - Y_{\tau\mu} \bar{\tau}_L \mu_R H + \text{h.c.} + \ldots \quad Y_{ij} = \frac{m_i}{v} \delta_{ij} + \frac{v^2}{\sqrt{2}\Lambda^2} [V_L \lambda' V_R^\dagger]_{ij}
\]

- No tuning between $\lambda$ and $\lambda'$ if $|Y_{\tau\mu} Y_{\mu\tau}| \lesssim \frac{m_\mu m_\tau}{v^2}$ etc. [Cheng, Sher, 1987]
- Present in many BSM models: multi-Higgs, RS (see below), ...
Low- and high-energy constraints

[Blankenburg et al., 2012; Harnik et al., 2012; Atwood et al., 2013; ...]

**Low energy**
- Quark couplings: meson ($K, D, B$) mixing
- Neutron EDM
- Lepton couplings: radiative penguins
  - $\ell_i \to \ell_j \gamma$
  - $\ell_i \to \ell_j \ell \ell$
  - $\mu e$ conversion, $(g - 2)_\ell$
  - $\ell$ EDM

**Direct observation in FV Higgs decay?**
- $H \to \ell_i \ell_j$
- $H \to t^* (\to bW)q$

**High energy**
- Single top production
- Same-sign $tt$ production
- (LEP)
- $t \to h + \text{jet}$
Limits on $Y_{fitj}$

<table>
<thead>
<tr>
<th>Technique</th>
<th>Coupling</th>
<th>Constraint</th>
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<tbody>
<tr>
<td>$D^0$ oscillations</td>
<td>$</td>
<td>Y_{ue}</td>
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<td>Y_{ue} Y_{cu}</td>
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<tr>
<td>$B_d^0$ oscillations</td>
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<td>Y_{db}</td>
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<td>Y_{db} Y_{bd}</td>
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<tr>
<td>$B_s^0$ oscillations</td>
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<td>Y_{sb}</td>
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<td></td>
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<td>Y_{sb} Y_{bs}</td>
</tr>
<tr>
<td>$K^0$ oscillations</td>
<td>$\text{Re}(Y_{ds}^2)$, $\text{Re}(Y_{sq}^2)$</td>
<td>$[-5.9 \ldots 5.6] \times 10^{-10}$</td>
</tr>
<tr>
<td></td>
<td>$\text{Im}(Y_{ds}^2)$, $\text{Im}(Y_{sq}^2)$</td>
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<tr>
<td></td>
<td>$\text{Re}(Y_{ds}^* Y_{sd})$</td>
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<tr>
<td>neutron EDM</td>
<td>$\text{Im}(Y_{we} Y_{wu})$</td>
<td>$&lt; 4.4 \times 10^{-8}$</td>
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[Harnik et al., 1209.1397v2]
## Limits on $Y_{fifj}$

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### Channel | Coupling | Bound |
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<td>$\mu \to e\gamma$</td>
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<tr>
<td>$\mu \to 3e$</td>
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</tr>
<tr>
<td>electron $g - 2$</td>
<td>$\text{Re}(Y_{ep}Y_{\mu e})$</td>
<td>$-0.019 \ldots 0.026$</td>
</tr>
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<td>Y_{\mu e} + Y_{e\mu}^*</td>
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<td>$\tau \to e\gamma$</td>
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[Harnik et al., 1209.1397v2]
Limits on $Y_{ij}$

- Indirect constraints preclude any collider signatures except in the $\tau$ and top sector.

- $\text{Br} (H \rightarrow \tau\mu) \sim 10\%$ and $\text{Br} (H \rightarrow \tau e) \sim 10\%$ still possible [Blankenburg et al., 2012]

  Could be excluded by dedicated LHC searches [Harnik et al., 2012]

- Caveat: LFV penguins can be generated at the scale $\Lambda$. 

M. Beneke (TU München), Flavour physics

Latsis Symposium, Zürich, 06 June 2013
Penguin transitions in the (minimal) RS model

Slice of AdS$_5$ in interval $[0, \pi]$ ($[1/k, 1/T]$ in conformal coordinates)
Minimal RS model: All SM fields except the Higgs in the bulk.
Potentially a theory of flavour.

- Higgs FCNC at tree-level due to mixing with KK excitations [Agashe, Perez, Soni, 2006; Azatov et al., 2009]
- Lepton- and quark penguin transitions [Csaki et al., 2010; Blanke et al., 2012], with WCHC [Delaunay et al., 2012]
- Complete 5D calculation of gauge-boson contribution to $g_\mu - 2$, and Higgs-exchange induced LFV. [MB, Dey, Rohrwild, 2012]

Wrong-chirality Higgs couplings (WCHC)

\[
\int d^4x \ [(\bar{L}\Phi)E + \text{h.c.}]_{z=1/T} = \int d^4x \ [(\bar{L}_L\Phi)E_R + (\bar{L}_R\Phi)E_L + \text{h.c.}]_{z=1/T}
\]

The WCHC $(\bar{L}_R\Phi)E_L$ vanishes for a brane-localized Higgs due to the boundary condition. Too naive!
Higgs FCNC and dipole operators

\[ \mathcal{L} = \frac{ce}{8\pi^2} \bar{\tau} \sigma_{\mu\nu} \mu F^{\mu\nu} + \text{h.c.} \]

\[ \Gamma(\tau \rightarrow \mu\gamma) = \frac{\alpha m_\tau^5 |c|^2}{64\pi^4} \]

Electroweak scale loop (anarchic 5D Yukawa) [Azatov et al., 2009]

\[ c \sim \frac{Y_{\tau\tau} Y_{\tau\mu}^*}{12m_H^2} \sim Y_\tau^2 \frac{\sqrt{m_\mu m_\tau}}{12T^2} \times \frac{m_\tau^2}{m_H^2} \]
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Electroweak scale loop (anarchic 5D Yukawa) [Azatov et al., 2009]

\[ c \sim \frac{Y_{\tau\tau} Y_{\tau\mu}^*}{12 m_H^2} \sim Y_2^2 \frac{\sqrt{m_\mu m_\tau}}{12 T^2} \times \frac{m_T^2}{m_H^2} \]

KK scale loop generates dim-6 \( \bar{L}_i \Phi \sigma_{\mu\nu} E_j F_{\mu\nu} \) operator (narrow bulk Higgs profile) [MB, Dey, Rohrwild, 2012]

\[ c \sim Y_2^2 \frac{\sqrt{m_\mu m_\tau}}{12 T^2} \]

Dominant. Decouples low-energy constraints from LFV Higgs decays.
Summary

I From the broad perspective flavour physics looks more SM-like than ever

II As do null searches at high-energy colliders supports the idea that the SM could be valid to very high scales

III Even if there is no new fundamental physics (yet) there is lots of fascinating physics

IV 20% NP effects often possible. Precision is important for flavour physics at LHCb and SuperBelle

V Constraints from flavour physics perhaps more important than ever though would have hoped for guidance from LHC discoveries

VI Top and Higgs add extra dimensions to flavour
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