Recent Topics in Flavour Phenomenology

(focus on B-decays)

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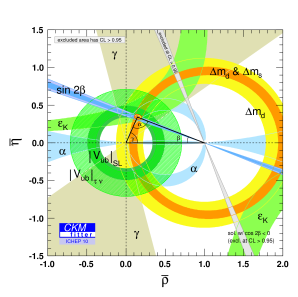
Collider Phenomenology 2011, Cambridge, 19 April 2011

Lessons on New Physics from the Flavour Sector



CKM Mechanism
Experimentally Confirmed. $\surd$

- Precision Flavour Observables constrain Parameter Space of NP Models. $(\surd)$
- Flavour Sector of New Physics@TeV must be highly Non-Generic. (!)
- Symmetry Principle $\rightarrow$ Minimal Flavour Violation (MFV): (?)
  - Paradigm: Flavour- and CP-Violation from NP still governed by V_{CKM} only (!?)
  - Book-keeping device: MFV expansion of NP flavour matrices.
  - Dynamical implementation: Spontaneously broken flavour symmetries (??)

[Buras; Ciucchini; ... D'Ambrosio et al.; ... TF/Mannel et al.; Grinstein/Redi/Villadoro; ...]

...but also: "Puzzles"/small Tensions in some B-Observables

- $|V_{cb}|_{\rm incl.}$ vs. $|V_{cb}|_{\rm excl.}$
- $|V_{ub}|_{\rm incl.}$ vs. $|V_{ub}|_{\rm excl.}$ vs. $|V_{ub}|_{\tau\nu}$
- Rare $b \to s$ Decays:
  - A_{CP} in $b \to s$ penguins
  - (A_{FB} in $B \to K^* \mu^+ \mu^-$)
  - ...
- Tensions in B_s-$\overline{B}_s$–mixing:
  - CP asymmetry from $B_s \to J/\psi\phi$
  - CP asymmetry in like-sign di-muon events from D0

...

Still room for NP → to be explored

Outline

1. Status of Inclusive B–Meson Decays
2. Exclusive Leptonic and Semi-leptonic B–Decays
3. New Physics in B_s–Meson Mixing?
4. Rare (Semi-) Leptonic B-Decays
5. Phenomenology of a Sequential 4^{th} Fermion Generation

1. Status of Inclusive B–Meson Decays: $B \to X_c \ell\nu$, $B \to X_u \ell\nu$, $B \to X_s\gamma$

Operator Product Expansion (moments of energy spectrum)

- Factorization based on expansion in $1/m_{b,c}$ and $\alpha_s(m_b)$
  - α_s^2 corrections to partonic rate [Melnikov, Czarnecki, Pak]
  - Tree-level expressions known to order $1/m_b^5$;
    systematics of "intrinsic charm" and "weak annihilation"
    [Bigi, Breidenbach, TF, Mannel, Turcyzk, Uraltsev, Zwicky,...]

Soft-Collinear Effective Theory (shape-function region – large recoil energy):

- Factorization theorems in SCET: $d\Gamma = H \cdot J \otimes S$
  - hard coefficient functions H — NNLO [Asatrian et al. 08; Beneke et al. 08; Bell 08]
  - collinear jet function J — NNLO [Becher/Neubert 05/06]
  - soft shape function S (aka PDF) — 2-loop RGE [Becher/Neubert 05]

- Determine: $|V_{cb}|_{\rm incl.} = (41.9 \pm 0.42_{\rm exp} \pm 0.59_{\rm th}) \cdot 10^{-3}$
  Determine: $|V_{ub}|_{\rm incl.} = (4.25 \pm 0.15_{\rm exp} \pm 0.20_{\rm th}) \cdot 10^{-3}$ [Kowalewski@BEAUTY2011]
- NP constraints from $B \to X_s\gamma$ [...; Andersen/Gardi 06; Misiak et al. 07; Becher/Neubert 07; ...]

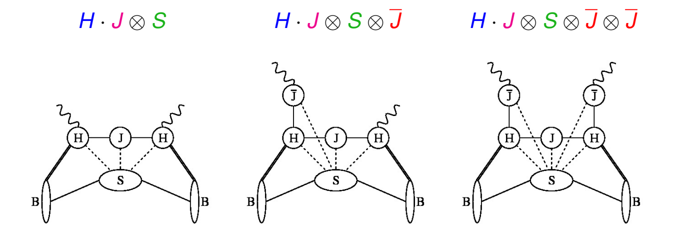
$B \to X_s\gamma$ and Resolved Photon Effects

[Benzke/Lee/Neubert/Paz 09-11]

New effects at sub-leading order in $1/m_b$ expansion:

- Photon does not couple directly to short-distance $b \to s$ transition.

$\Rightarrow$ New Factorization Theorem:



Features of "resolved" photon contribution:

- New jet function $\bar{J}$ and soft functions — difficult to estimate
- Leading mechanism for CP Violation in the SM: $-0.5\% < \mathcal{A}^{\rm SM}_{X_s\gamma} < 2.8\%$
- Better Null-Tests of the SM: $(\mathcal{A}_{X_s^-\gamma} - \mathcal{A}_{X_s^0\gamma})$ or $\mathcal{A}_{X_{s+d}\gamma}$

2. Exclusive Leptonic and Semi-leptonic B–Decays

$|V_{cb}|$ from $B \to D(D^*)\ell\nu$ [Kowalewski@BEAUTY2011]

- Decay rate $d\Gamma \propto |F(q^2)|^2 \cdot |V_{cb}|^2$ requires $B \to D^{(*)}$ form factor
- $F(q^2_{\rm max}) = (1 + \text{corrections})$ from HQET and lattice/sum rules

$$|V_{cb}|_{\rm excl} = (38.9 \pm 0.9_{\rm exp} \pm 0.6_{\rm th}) \cdot 10^{-3}$$

$|V_{ub}|$ from $B \to \pi\ell\nu$ [Kowalewski@BEAUTY2011]

- $B \to \pi$ form factor normalization not fixed by HQET symmetries
- Extraction of $|V_{ub}|$ relies on lattice/sum rules and appropriate form-factor parameterisations (see below).

$$|V_{ub}|_{\rm excl} = (3.25 \pm 0.12_{\rm exp} \pm 0.28_{\rm th}) \cdot 10^{-3}$$ [BaBar+Belle+FNAL/MILC]

$|V_{ub}|$ from $B \to \tau\nu$ [Mannel@BEAUTY2011]

- Requires B-meson decay constant f_B (lattice).
- Experimental value for $B \to \tau\nu$ compared to $B \to \pi\ell\nu$ factor of 2 larger than theoretical prediction !?

Example: $|V_{ub}|$ and NP with Right-handed Currents

[Buras/Gemmler/Isidori 10], see also [Crivellin 09]

Effective theory approach:

- New CKM'–Matrix $\widetilde{V}$ in the right-handed sector,
- Suppression by small parameter ϵ_R
- ...

$$|V_{ub}|_{B\to X_u\ell\nu} \longrightarrow \sqrt{|V_{ub}|^2 + \epsilon_R^2\,|\widetilde{V}_{ub}|^2}$$

$$|V_{ub}|_{B\to\pi\ell\nu} \longrightarrow |V_{ub} + \epsilon_R\,\widetilde{V}_{ub}|$$

$$|V_{ub}|_{B\to\tau\nu} \longrightarrow |V_{ub} - \epsilon_R\,\widetilde{V}_{ub}|$$

Further:

- meson mixing
- $Z \to b\bar{b}$
- $B_{s,d} \to \mu\mu$
- $B \to X_s\nu\bar{\nu}$ (excl. & incl.)
- $K \to \pi\nu\bar{\nu}$
- $S_{\psi\phi}$ and $S_{\phi K}$

Determination of CKM and CKM' parameters:

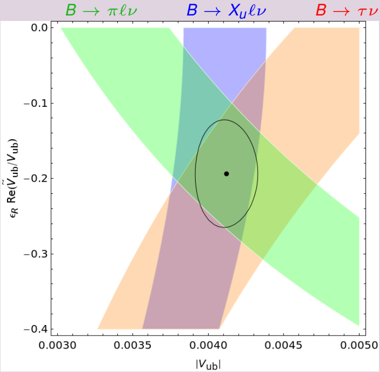
$$\Rightarrow \qquad |V_{ub}| = (4.1 \pm 0.2) \cdot 10^{-3} \,,$$

$$\epsilon_R \, \mathrm{Re}\left(\frac{\widetilde{V}_{ub}}{V_{ub}}\right) = -0.19 \pm 0.07$$

- 2.7σ for RH current

  (tension between $\sin 2\beta_{\rm fit}$ and $S_{\psi K}$ remains)

[Buras/Gemmler/Isidori 10]



(RH currents in $b \to c\ell\nu$ can also be studied independently from moment analysis in $B \to X_c\ell\nu$ [Feger/Mannel et al. 10])

3. New Physics in B_s-$\overline{B}_s$–Mixing ?

- D0 measures a combination of semi-leptonic CP asymmetries:

$$A_{\rm SL}^{\rm D0} = (0.506 \pm 0.043)\, a_{\rm fs}^d + (0.494 \pm 0.043)\, a_{\rm fs}^s$$
$$= -0.00957 \pm 0.00251 \pm 0.00146$$

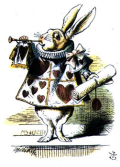
which significantly deviates from the SM estimate

$$A_{\rm SL}^{\rm SM} = -(2.0 \pm 0.3) \cdot 10^{-4} \qquad \text{[Lenz/Nierste 11]}$$

- Combined D0/CDF results on $S_{\psi\phi}$ yield

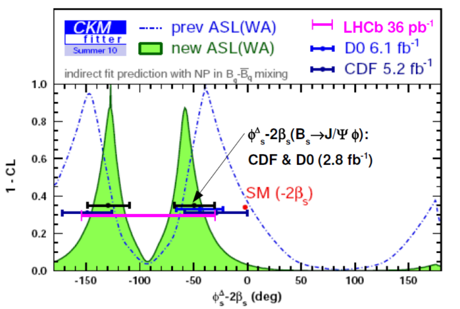
$$S_{\psi\phi} = 0.74^{+0.19}_{-0.23}$$

which are significantly larger than the SM result, $S_{\psi\phi}^{\rm SM} = \sin 2\beta_s \approx 0$.



Fit to NP Phase in B_s–Mixing

[Lacker@BEAUTY2011]



LHCb catches up quickly:

[see talk by Val Gibson]

- $-2\beta_s^{\psi\phi}\big|_{\rm eff} \in [-2.7, -0.5]$ @68% CL [Lambert@BEAUTY2011]
- LHCb will also be measuring

$$2\,\Delta A_{\rm SL} = a_{\rm fs}^s - a_{\rm fs}^d$$

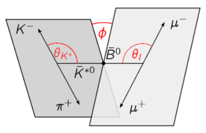
for which the SM prediction reads $(4.3 \pm 0.7) \cdot 10^{-4}$.

4. Rare (Semi-) Leptonic B-Decays

- Based on rare $b \to s$ or $b \to d$ FCNCs $\Rightarrow$ NP Sensitivity
  - New sources of Flavour/CP-Violation beyond the SM

$$\mathcal{L} \stackrel{?}{=} \mathcal{L}_{\rm SM} + \sum_i \frac{C_i^d}{\Lambda_{\rm NP}^{4-d}} \, \mathcal{O}_i^{(d)}$$

- HQET/SCET symmetries reduce # of independent form factors.
- Variety of (theoretically controlable) Observables:
  - FB asymmetry in $B \to K^* \mu^+ \mu^-$
  - Isospin asymmetry in $B \to K^* \mu^+ \mu^-$
  - Angular asymmetries in $B \to K^*(K\pi) \mu^+ \mu^-$



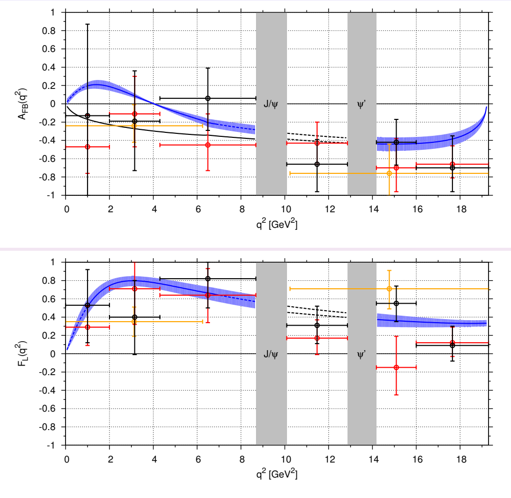
  - Decay rates for $B \to K^{(*)} \nu \bar{\nu}$
  - Decay rates for $B_q \to \mu^+ \mu^-$
  - ...

[...Bobeth/Hiller et al., Beneke/TF/Seidel, Egede/Hurth/Krüger/Matias et al., Altmannshofer/Ball/Bharucha/Buras/Straub et al. ...]

[for a recent analysis, see also: Alok et al, 1103.5344]

Example: FB-Asymmetry and Longitudinal Fraction in $B \to K^* \mu^+ \mu^-$

[Bobeth/Hiller/van Dyk 10]



— SM   + Belle   + Babar   + CDF

Theory for $B \to K^{(*)}\mu^+\mu^-$ Decays

General amplitude for $B \to K^{(*)}\mu\mu$

- Hadronic amplitude multiplying the lepton axial-vector current $\longrightarrow C_{10} \times$ (form factor)
- Hadronic amplitude multiplying the lepton vector current:

$$C_9 \, \langle \bar{K}^{(*)}|\bar{s}\gamma^\mu(1-\gamma_5)b|\bar{B}\rangle \qquad \longrightarrow C_9 \times \text{(form factor)}$$

$$+\, C_7 \, \frac{2im_b\, q_\lambda}{q^2} \, \langle \bar{K}^{(*)}|\bar{s}\sigma^{\lambda\mu}(1+\gamma_5)b|\bar{B}\rangle \qquad \longrightarrow C_7 \times \text{(form factor)}$$

$$+\, \langle \bar{K}^{(*)}|\, \mathcal{K}_H^\mu(q)\, |\bar{B}\rangle \qquad \longrightarrow \begin{cases} q^2 \ll 4m_c^2 & : \ \text{QCD factorization} \\ q^2 \gg 4m_c^2 & : \ \text{OPE} \end{cases}$$

  - $\mathcal{K}_H^\mu(q)$ from non-leptonic part of $H_{\rm eff}(b \to s)$
  - leading order QCDF/OPE: sufficient to replace $C_9 \to C_9^{\rm eff}(q)$
  - sub-leading order in α_s and/or $1/m_b$: "Non-factorizable contributions"

Potential Issue: Duality violation from $B \to V(\to \mu^+\mu^-)K^*$ with $V = J/\psi, \psi', \ldots$

Duality Violation in $B \to K^{(*)}\mu^+\mu^-$ at high-q^2

[Beylich/Buchalla/TF 11]   see also [Buchalla/Isidori 98, Grinstein/Pirjol 04, Khodjamirian et al. 10]

OPE for high-q^2 region: (above $c\bar{c}$ resonances)

- leading term in OPE from dim-3 operators, ($\to$ standard form factors)
  α_s corrections to $\langle \mathcal{K}_H^\mu \rangle_{\rm dim-3}$ known (and important) [. . . Seidel 04, Greub/Pilipp/Schüpbach 08]
- contributions from dim-4 operators suppressed $\alpha_s \frac{m_s}{m_b} \sim 0.5\%$
- contributions from dim-5 operators $\langle \bar{s} G^{\mu\nu} b \rangle$ estimated $< 1\%$
- dim-6 operators include weak annihilation effects, negligible at high-q^2 $\mathcal{O}(0.1\%)$

Duality-violating effects at high-q^2:

- Estimated on the basis of a model for an inifinite series of charm resonances, fitted to experimental R-ratio [Shifman 2000]
- Uncertainty on partially integrated decay rate ($q^2 \geq 15$ GeV^2) $\pm 2\%$

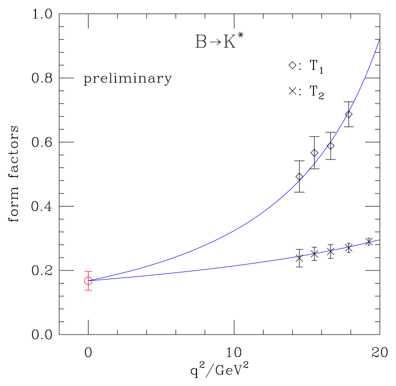
Duality violation for differential rate (point-by-point) remains model-dependent.

High-q^2 region of $B \to K^{(*)}\mu^+\mu^-$ under excellent theoretical control

$B \to K^{(*)}$ Form Factors from Lattice-QCD

[Liu et al, 1101.2726, 0911.2370, see also Wingate@BEAUTY2011]

Tensor Form Factors $T_{1,2}$ for $B \to K^*$ $(T_1(0) \equiv T_2(0))$



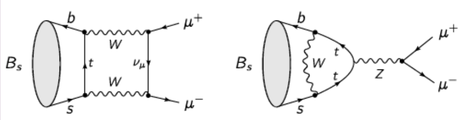
- unquenchend configurations
- moving NRQCD
  (2+1 flavours, $\mathcal{O}(a^2)$ tadpole-improved, staggered fermions, $m_\pi^{\text{simul.}} \geq 300$ MeV, physical m_b)

- Lattice results can be combined with LCSR estimates for small q^2, using truncated "series expansion" and unitarity bounds
  [Bharucha/TF/Wick 2010]

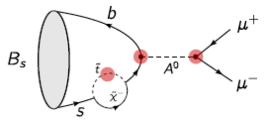
Phenomenology for $B_q \to \mu^+\mu^-$

- Hadronic uncertainty from decay constants f_{B_q} only.
- Helicity suppression in the SM:

$$\mathcal{B}(B_s \to \mu^+\mu^-)_{\rm SM} \sim 3 \cdot 10^{-9}\,, \qquad \mathcal{B}(B_d \to \mu^+\mu^-)_{\rm SM} \sim 0.1 \cdot 10^{-9}$$

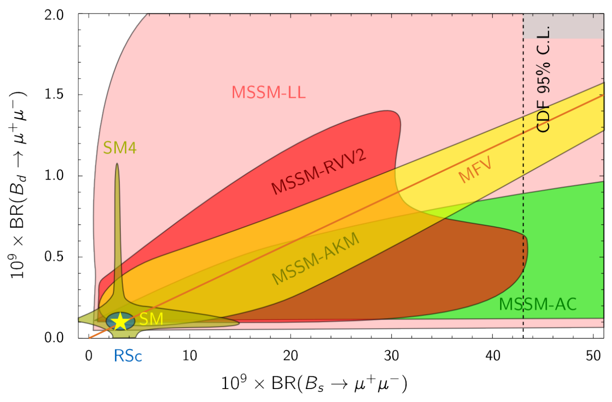


- Sizeable NP contributions possible, in particular for large $\tan\beta$:
  $\Rightarrow \mathcal{B}(B_s \to \mu^+\mu^-)_{\rm exp} < 10^{-8}$ would already rule out a number of NP models
- Correlations between $B_s \to \mu^+\mu^-$ and $B_d \to \mu^+\mu^-$
  as a test of Minimal Flavour Violation hypothesis (see below).



Correlation $B_s \to \mu\mu$ vs. $B_d \to \mu\mu$

- Minimal Flavour Violation (MFV): $\frac{\mathcal{B}(B_s \to \mu^+\mu^-)}{\mathcal{B}(B_d \to \mu^+\mu^-)} \simeq \frac{|V_{ts}|^2}{|V_{td}|^2}$
- 4th Generation Model [Buras et al. 10]
- SUSY Flavour Scenarios [Altmannshofer et al. 10]



[Straub@BEAUTY2011]

5. Phenomenology of a Sequential 4$^{\text{th}}$ Fermion Generation

- Add another Quark-Family: $(t'_L, b'_L),\ t'_R,\ b'_R$

  with $m_{t'} \sim (300 - 600)\ \text{GeV}$ and $m_{b'} \simeq m_{t'} - 50\ \text{GeV}$.

- Quark mixing matrix contains
  - 3 new mixing angles $\theta_{14}, \theta_{24}, \theta_{34}$
  - 2 new CP-phases δ_{14}, δ_{24}

MFV Perspective:

- Generic O(1) Angles: Excluded
- Consistency Conditions in Next-to-minimal MFV

[TF/Mannel 06]

$$\theta_{i4}\theta_{j4} \lesssim \theta_{ij}$$ ($i, j = 1..3$ for SM quarks)

- MFV is recovered only for $\theta_{i4} \to 0$.

Constraints from Flavour Observables

[Buras/Duling/TF/Heidsieck/Promberger/Recksiegel 10]

also: [Bobrowski/Lenz/Riedl/Rohrwild, Soni et al. ...]

- Tree-level decays: $|V_{ud}|, |V_{us}|, |V_{ub}|, |V_{cd}|, |V_{cs}|$
  together with constraints on CKM-unitarity, already imply

$$\sin\theta_{14} < 0.04; \quad \sin\theta_{24} < 0.17; \quad \sin\theta_{34} < 0.27$$

- Meson-mixing: $\epsilon_K, \Delta M_K, \Delta M_{B_d}, \Delta M_{B_s}, S_{\psi K_s}$ (@ 1σ)
- Rare decays: $B \to X_s\gamma, X_s\ell^+\ell^-, B_s \to \mu^+\mu^-, K^\pm \to \pi^\pm\nu\bar{\nu}$

  (looser bounds)

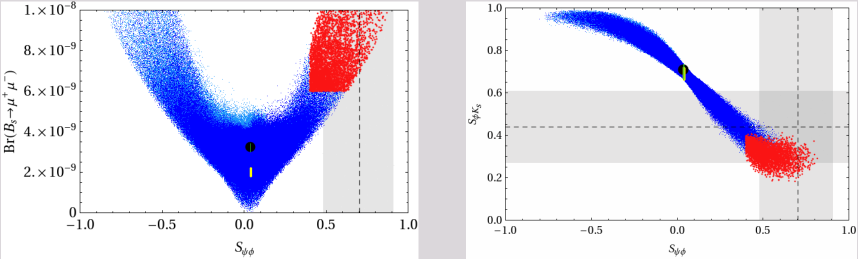
- Also ϵ'_K relevant (although with larger hadronic uncertainties)

Further constraints on 4G parameter space, incl. CP-phases.
Correlations between various flavour observables.

$\to$ The bulk of consistent parameter points satifies the nMFV Criteria.

Example: $\mathcal{B}(B_s \to \mu\nu)$ and $S_{\phi K_S}$ vs. $S_{\psi\phi}$:

Without constraint from ϵ'_K:



Clear correlations

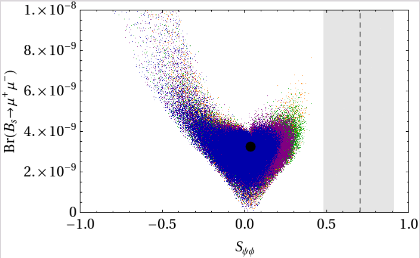
Colour Coding (B- and K-observables):

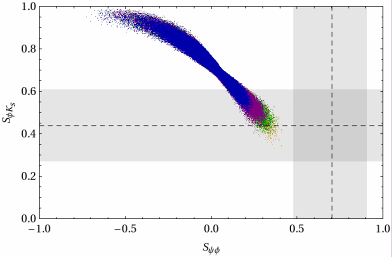
- (yellow) $S_{\psi\phi} = 0.04 \pm 0.01$ and $\mathrm{Br}(B_s \to \mu^+\mu^-) = (2 \pm 0.2) \cdot 10^{-9}$
- (red) $S_{\psi\phi} > 0.4$ and $\mathrm{Br}(B_s \to \mu^+\mu^-) > 6 \cdot 10^{-9}$
- (light blue) $\mathrm{Br}(K_L \to \pi^0\bar{\nu}\nu) > 2 \cdot 10^{-10}$ (blue) $\mathrm{Br}(K_L \to \pi^0\bar{\nu}\nu) < 2 \cdot 10^{-10}$

[Buras et al., arXiv:1002.2126 [hep-ph], arXiv:1004.4565 [hep-ph]]

Example: $\mathcal{B}(B_s \to \mu\nu)$ and $S_{\phi K_S}$ vs. $S_{\psi\phi}$:

Including constraint from ϵ'_K:





Very large $S_{\psi\phi}$ not possible, if ϵ'_K constraint taken into account

Colour Coding (hadronic matrix elements):

- $R_6 = 1.0$, $R_8 = 1.0$
- $R_6 = 1.5$, $R_8 = 0.8$
- $R_6 = 2.0$, $R_8 = 1.0$
- $R_6 = 1.5$, $R_8 = 0.5$

[Buras et al., arXiv:1002.2126 [hep-ph], arXiv:1004.4565 [hep-ph]]

Outlook: Prospects for Flavour Phenomenology in the LHC Era

LHCb is already performing extremely well . . . (ATLAS and CMS to follow)

- Many promising observables . . .
- The next year will be very exciting for flavour physics . . . [Uwer@BEAUTY2011]

Theory will continue to catch up . . .

- Control on factorization and perturbative uncertainties.
- Hadronic parameters (combining lattice/LCSR/exp. data).
- $SU(3)$ amplitude relations, including B_s decay modes.

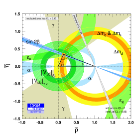
Various ideas on extensions of the SM . . .

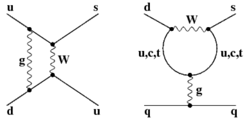
- Identification of NP-sensitive observables.
- Constraints on parameter space of concrete NP models.
- Correlations between NP observables.

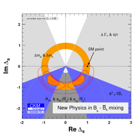
Challenge: Interpretation of combined data on flavour and high-$p_\perp$ observables !

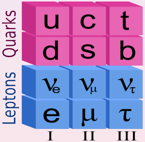
Theoretical Insight from Flavour Phenomenology I:

- Precision Tests of the CKM Mechanism in the SM
- Sharpening the Theoretical Tools for Perturbative QCD Calculations
- Hadronic Structure and Non-perturbative Calculations
- Indirect Search for New Physics in Rare Decays
- Shedding Light on the Systematics of Flavour Violation in SM/NP









Theoretical Insight from Flavour Phenomenology II:

Flavour Physics expects Sunny Days !

Backup Slides

Factorization

Flavour Transitions induced by Weak Gauge Bosons (or potential NP):

- Weak effective Hamiltonian: $H_{\rm eff} \propto \sum_i C_i(\mu)\mathcal{O}_i$
- Wilson Coefficients $C_i(m_b)$ in (RG-improved) Perturbation Theory.
  Contain all the information about short-distance dynamics !
- Hadronic Matrix Elements $\langle h_1 h_2 \cdots |\mathcal{O}_i| B\rangle \quad \Rightarrow \quad \ldots$

$\ldots \quad \Rightarrow \quad$ Treatment of Hadronic Matrix Elements:

- Reduce to (more) universal quantities, using
  Factorization Theorems based on the Heavy-Quark Expansion:
  - Heavy-quark effective theory (HQET) for small hadronic recoil energy.
  - Soft-collinear effective theory (SCET) for large recoil energy ($\rightarrow$ jets).
- (irreducible) Hadronic Parameters (approximately) cancel in certain Ratios:
  - time-dependent CP asymmetry in $B \rightarrow J/\psi K_S$
  - isospin-symmetry relations for $B \rightarrow \pi\pi$ decays
  - form-factor relations in $B \rightarrow K^* \mu^+ \mu^-$
  - ...

Hadronic Matrix Elements in B-Decays

Theoretical input for:
partial decay rates; CP-, isospin-, FB-, angular asymmetries, ...

- Leptonic decay constants: f_{B,B_s}
- Meson mixing parameters: B_{B,B_s}
- Exclusive transition form factors: $F^{B\to M}(q^2)$
- HQET parameters: m_b, $\frac{\lambda_{1,2}}{m_b}$ ...
- Hadronic light-cone distribution amplitudes: $\phi_\pi(u)$, $\phi_B(\omega)$
- Inclusive shape functions ($\equiv$ PDFs): $S(k)$
- ...

Determination of hadronic matrix elements:

- from Lattice QCD
- from (light-cone) QCD Sum Rules
- from Experiment (on the basis of factorization theorems)

Series Expansion for generic form factor $F(t = q^2)$:

[Boyd, Grinstein, Lebed, Savage, Caprini, Lellouch, Neubert, Becher, Hill, ...]

- Conformal Mapping:

$$z = z(t, t_0) = \frac{\sqrt{t_+ - t} - \sqrt{t_- - t_0}}{\sqrt{t_+ - t} + \sqrt{t_- - t_0}}\,, \qquad |z| \ll 1$$

with $t_\pm = (m_H \pm m_L)^2$ and $0 \leq t_0 < t_-$.

- (truncated) Series Expansion:

$$F(t) = (\text{pre-factor})(\text{t}) \times \sum_{i=0}^{N} \alpha_i \cdot z^i$$

(pre-factor contains analytic structure from resonances outside the decay region)

- Coefficients α_i constrained by “Dispersive Bounds”:

$$\sum_{i=0}^{N} |\alpha_i|^2 \leq 1$$

(from calculation of correlation functions with the corresponding decay currents)

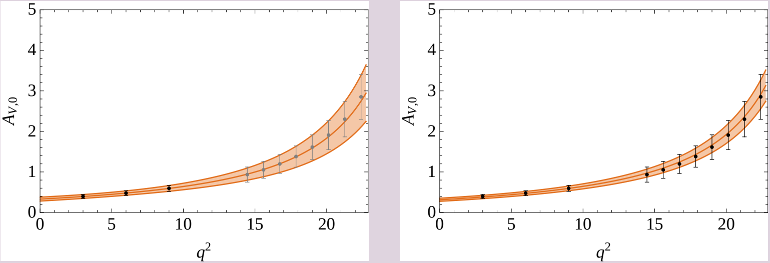
(Heavy-to-light) Form Factor Fits with Series Expansion

[Bharucha/TF/Wick 2010]

- FF at small momentum transfer $t = q^2$: from LCSR approach [QCDSF 0903.1664]
- FF at large momentum transfer $t = q^2$: Lattice QCD estimates [Ball/Zwicky 04]
- Interpolation: Truncated Series Expansion $(N = 1)$

Example: $B \to K$ transition form factors (vector current: $A_{V,0}(q^2) \equiv f_+(q^2)$)

LCSR only | LCSR + Lattice



Charmless Non-Leptonic B-Decays

- Generic $B \to M_1 M_2$ amplitude can be written in terms of Topological Amplitudes:

  Colour-allowed and colour-suppressed “Tree“ or ”Penguin“

- In the SM, the relative weak phase is given by the CKM angle γ

- Different (partially controversial) approaches to estimate strong interaction effects

  QCD factorization / SCET, ”perturbative QCD“

  - systematic calculation of perturbative corrections ?
  - size/reliability of $1/m_b$ power corrections ?
  - reliable calculation of colour-suppressed amplitudes ?
  - size of strong re-scattering phases ?

  [Beneke et al. 99; Bauer et al. 04; Keum et al. 00; . . .]

- Phenomenological analyses make use of (approximate) flavour symmetries of QCD:
  - Isospin symmetry
  - $SU(3)$ flavour symmetry $\longleftarrow$ hadronic B_s-decays!

  [Fleischer/Zupan et al., Zupan@BEAUTY2011]

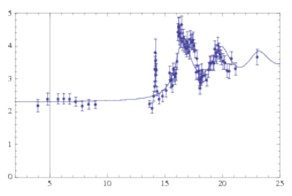
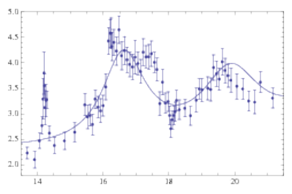
Modelling duality violation from charm-loop in $B \to K^{(*)}\mu^+\mu^-$

- Assume trajectory of charmonium resonances: $M_n^2 = n\lambda^2 + M_0^2$.
  (narrow resonances to be considered separately)

$\to$ Ansatz for R-ratio in the $c\bar{c}$-region:

$$R = R_{\text{light}} - \frac{4}{3}\,\frac{1}{(1-b/\pi)\,\pi}\,\mathrm{Im}\,\psi(3+z)\,, \qquad z = \left(-\frac{q^2 - 4m_c^2 + i\epsilon}{\lambda^2}\right)^{1-b/\pi}$$

- (crude) Fit to BES data :
  - $R_{\text{light}} = 2.31$, from below charm threshold.
  - $m_c = 1.33$ GeV.
  - $\lambda^2 = 3.08\ \text{GeV}^2$, from average distance of (broad) resonances.
  - $b = 0.082$, from average width of (broad) resonances.

- Use same parameters to describe charm-contribution to $\langle \mathcal{K}_H^\mu \rangle$
  (assuming pessimistic scenario where all resonances contribute coherently)

[Beylich/Buchalla/TF, arXiv:1101.5118]

NP Sensitivity for Wilson Coefficients in $b \to s\gamma, s\ell^+\ell^-$

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

which operators are relevant in which decay?

		$B \to X_s\gamma$	$B \to K^*\mu^+\mu^-$	$B_s \to \mu^+\mu^-$
mag. dipole operators	$Q_7^{(\prime)} \sim m_b(\bar{s}_{L,R}\sigma_{\mu\nu} b_{R,L})F^{\mu\nu}$	X	X	
	$Q_8^{(\prime)} \sim m_b(\bar{s}_{L,R}\sigma_{\mu\nu} T^a b_{R,L})G^{\mu\nu\, a}$	X	X	
semileptonic operators	$Q_9^{(\prime)} \sim (\bar{s}b)_{V\mp A}(\bar{\ell}\ell)_V$		X	
	$Q_{10}^{(\prime)} \sim (\bar{s}b)_{V\mp A}(\bar{\ell}\ell)_A$		X	X
scalar operators	$Q_S^{(\prime)} \sim m_b(\bar{s}b)_{S\pm P}(\bar{\ell}\ell)_S$			X
	$Q_P^{(\prime)} \sim m_b(\bar{s}b)_{S\pm P}(\bar{\ell}\ell)_P$			X

David Straub Beauty 2011, Amsterdam

[Straub@BEAUTY2011]

Examples for "Allowed" Patterns of 4G Mixing–Matrix

$$V^{4G} \sim \begin{pmatrix} 1 & \lambda & \lambda^3 & \lambda^4 \\ \lambda & 1 & \lambda^2 & \lambda^3 \\ \lambda^3 & \lambda^2 & 1 & \lambda \\ \lambda^4 & \lambda^3 & \lambda & 1 \end{pmatrix} \quad \sim \begin{pmatrix} 1 & \lambda & \lambda^3 & \lambda^2 \\ \lambda & 1 & \lambda^2 & \lambda \\ \lambda^3 & \lambda^2 & 1 & \lambda \\ \lambda^2 & \lambda & \lambda & 1 \end{pmatrix}$$

$$V^{4G} \sim \begin{pmatrix} 1 & \lambda & \lambda^3 & \lambda^2 \\ \lambda & 1 & \lambda^2 & \lambda^3 \\ \lambda^3 & \lambda^2 & 1 & \lambda \\ \lambda^2 & \lambda^3 & \lambda & 1 \end{pmatrix} \quad \sim \begin{pmatrix} 1 & \lambda & \lambda^3 & \lambda^3 \\ \lambda & 1 & \lambda^2 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 & \lambda \\ \lambda^3 & \lambda^2 & \lambda & 1 \end{pmatrix}$$

→ Scaling of new flavour coefficients in CP-violating observables

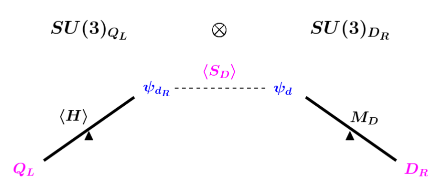
Scenario $n_1 n_2 n_3$	(a) 431	(b) 211	(c) 231	(d) 321
$\mathrm{Im}\left[\lambda_t^{(d)}/\lambda_t^{(d)}\vert_{\mathrm{SM}}\right] \simeq -\mathrm{Im}\left[\lambda_{t'}^{(d)}/\lambda_t^{(d)}\vert_{\mathrm{SM}}\right]$	$\mathcal{O}(\lambda^2)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}(\lambda)$
$\mathrm{Im}\left[\lambda_t^{(s)}/\lambda_t^{(s)}\vert_{\mathrm{SM}}\right] \simeq -\mathrm{Im}\left[\lambda_{t'}^{(s)}/\lambda_t^{(s)}\vert_{\mathrm{SM}}\right]$	$\mathcal{O}(\lambda^2)$	$\mathcal{O}(1)$	$\mathcal{O}(\lambda^2)$	$\mathcal{O}(\lambda)$
$\mathrm{Im}\left[\lambda_t^{(K)}/\lambda_t^{(K)}\vert_{\mathrm{SM}}\right]$	$\mathcal{O}(\lambda^2)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}(\lambda)$
$\mathrm{Im}\left[\lambda_{t'}^{(K)}/\lambda_t^{(K)}\vert_{\mathrm{SM}}\right]$	$\mathcal{O}(\lambda^2)$	$\mathcal{O}(\lambda^{-2})$	$\mathcal{O}(1)$	$\mathcal{O}(1)$
$\mathrm{Im}\left[\lambda_c^{(d)}/\lambda_c^{(d)}\vert_{\mathrm{SM}}\right] \simeq \mathrm{Im}\left[\lambda_c^{(K)}/\lambda_c^{(K)}\vert_{\mathrm{SM}}\right]$	$\mathcal{O}(\lambda^6)$	$\mathcal{O}(\lambda^2)$	$\mathcal{O}(\lambda^4)$	$\mathcal{O}(\lambda^4)$
$\mathrm{Im}\left[\lambda_c^{(s)}/\lambda_c^{(s)}\vert_{\mathrm{SM}}\right]$	$\mathcal{O}(\lambda^8)$	$\mathcal{O}(\lambda^4)$	$\mathcal{O}(\lambda^6)$	$\mathcal{O}(\lambda^6)$

where $\lambda = \sin\theta_C \sim 0.2$.

Yukawa Couplings in Models with Gauged Flavour Symmetries

Idea:

- Additional fermions required to cancel chiral gauge anomalies.
  [Grinstein/Redi/Villadoro; Albrecht/TF/Mannel]
- VEV of scalar spurion fields S_i break flavour symmetry and give masses to new fermions.
- SM Yukawa couplings effectively produced from see-saw mechanism.



- E.g. renormalizable Lagrangian in down-quark sector:

$$\mathcal{L} \ni \overline{Q}_L \, H \, \psi_{d_R} + \overline{\psi}_d \, S_D \, \psi_{d_R} + M_D \, \overline{\psi}_d \, D_R + \text{h.c.}$$

- Integrate out ψ_{d,d_R}, assuming $\langle H \rangle \ll M_D \ll \langle S_D \rangle$:

$$\mathcal{L}_{\rm eff} \ni -\overline{Q}_L \, \langle H \rangle \, M_D \, \langle S_D \rangle^{-1} \, D_R + \text{h.c.}$$