Flavour Physics in the LHC Era
Lecture 3 of 3

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Contents

• Part 1
  – Why is flavour physics interesting?

• Part 2
  – What do we know from previous experiments?

• Part 3
  – What do we hope to learn from current and future heavy flavour experiments?

Today I'd better cover Part 3

(no really)
Direct CP violation

- Condition for DCPV: $|\bar{A}/A| \neq 1$
- Need $\bar{A}$ and $A$ to consist of (at least) two parts
  - with different weak ($\phi$) and strong ($\delta$) phases
- Often realised by “tree” and “penguin” diagrams

$$A = |T|e^{i(\delta_T - \phi_T)} + |P|e^{i(\delta_P - \phi_P)} \quad \bar{A} = |T|e^{i(\delta_T + \phi_T)} + |P|e^{i(\delta_P + \phi_P)}$$

$$A_{CP} = \frac{|\bar{A}|^2 - |A|^2}{|\bar{A}|^2 + |A|^2} = \frac{2|T||P|\sin(\delta_T - \delta_P)\sin(\phi_T - \phi_P)}{|T|^2 + |P|^2 + 2|T||P|\cos(\delta_T - \delta_P)\cos(\phi_T - \phi_P)}$$

Example: $B \to K\pi$
(weak phase difference is $\gamma$)
The famous penguin story

Penguin diagram

From Wikipedia, the free encyclopedia

In quantum field theory, penguin diagrams are a class of Feynman diagrams which are important for understanding CP violating processes in the standard model. They were first isolated and studied by Mikhail Shifman, Arkady Vainshtein, and Valentin Zakharov.[1] The processes which they describe were first directly observed in 1991 and 1994 by the CLEO collaboration.

Origin of the name

John Ellis was the first to refer to a certain class of Feynman diagrams as penguin diagrams, due in part to their shape, and in part to a legendary bar-room bet with Melissa Franklin. According to John Ellis,[2]

“Mary K. [Gaillard], Dimitri [Nanopoulos] and I first got interested in what are now called penguin diagrams while we were studying CP violation in the Standard Model in 1976... The penguin name came in 1977, as follows.

In the spring of 1977, Mike Chanowitz, Mary K and I wrote a paper on GUTs predicting the b quark mass before it was found. When it was found a few weeks later, Mary K, Dimitri, Serge Rudaz and I immediately started working on its phenomenology. That summer, there was a student at CERN, Melissa Franklin who is now an experimentalist at Harvard. One evening, she, I, and Serge went to a pub, and she and I started a game of darts. We made a bet that if I lost I had to put the word penguin into my next paper. She actually left the darts game before the end, and was replaced by Serge, who beat me. Nevertheless, I felt obligated to carry out the conditions of the bet.

For some time, it was not clear to me how to get the word into this b quark paper that we were writing at the time. Then, one evening, after working at CERN, I stopped on my way back to my apartment to visit some friends living in Meyrin where I smoked some illegal substance. Later, when I got back to my apartment and continued working on our paper, I had a sudden flash that the famous diagrams look like penguins. So we put the name into our paper, and the rest, as they say, is history.”

Example of a penguin diagram
The famous penguin story

Penguin diagram
From Wikipedia, the free encyclopedia

In quantum field theory, **penguin diagrams** are a class of **Feynman diagrams** which are important for understanding **CP violating** processes in the **standard model**.

They were first isolated and studied by **John Ellis** in 1991 and 1994 by the **CLEO** collaboration.

Origin of the name

John Ellis was the first to refer to a certain draw as a penguin diagram, and in part to a legendary bar-room bet.

"Mary K. [Gaillard], Dimitri [Rudaz] and I immediately started working on the quark mass before it was fully clear. When I was at CERN, Melissa was a student at CERN, Melissa, she, I, and Serge went to a bar, and I had to put the word penguin on it in the end, and was replaced by the conditions of the bet.

For some time, it was not very clear what was going on. Then, one evening, after working at CERN, I stopped on my way back to my apartment to visit some friends living in Meyrin where I smoked some illegal substance.

Later, when I got back to my apartment and continued working on our paper, I had a sudden flash that the famous diagrams look like penguins. So we put the name into our paper, and the rest, as they say, is history."
Direct CP asymmetries in charmless hadronic B decays

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Flavour Physics
Direct CP violation in $B \rightarrow K\pi$

- Direct CP violation in $B \rightarrow K\pi$ sensitive to $\gamma$
  - too many hadronic parameters $\Rightarrow$ need theory input
  - NB. interesting deviation from naïve expectation

\[
A_{CP}(K^{-}\pi^{+}) = -0.087 \pm 0.008 \\
A_{CP}(K^{-}\pi^{0}) = +0.037 \pm 0.021
\]

“K\pi puzzle”

Could be a sign of new physics …

… first need to rule out possibility of larger than expected QCD corrections

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Heavy Flavour Physics
Clean observables in $B \rightarrow K\pi$ (etc.)

- Measure more $B_{u,d} \rightarrow K\pi$ decays & relate by isospin
- Perform similar analysis on $B \rightarrow K^*\pi$ &/or $B \rightarrow K\rho$
  - Dalitz plot analyses of $K\pi\pi$ final states extract both amplitudes and relative phases $\rightarrow$ more observables
- Measure $B_s \rightarrow KK$ decays & relate by $U$-spin
  - e.g. relation between time-dependent CP violation observables in $B_s \rightarrow K^+K^-$ and $B^0 \rightarrow \pi^+\pi^-$
- Dalitz plot analyses of $B_s \rightarrow KK\pi$

Note: flavour symmetries very useful
But, still get theory error from symmetry breaking (difficult to evaluate)
… data driven methods will win in the end (unless miracle breakthrough)
Latest results on multibody charmless B decays

B → KKK

LHCb-CONF-2012-018

Large CP violation effects with strong variation across the Dalitz plot
Detailed studies will be necessary to understand origin of these effects
$B \rightarrow h^+ h'^-$ at hadron colliders

- Excellent channel to profit from displaced vertex trigger
- Particle ID extremely important

CDF PRL 103 (2009) 031801

LHCb arXiv:1202.6251

LHCb-CONF-2012-007
$$B^0 \rightarrow \pi^+\pi^- \; & \; B^0_s \rightarrow K^+K^-$$

First CP violation measurements in these channels at a hadron collider ($B^0 \rightarrow \pi^+\pi^-$) / ever ($B^0_s \rightarrow K^+K^-$)

LHCb-CONF-2012-007

5359 ± 96 signal events

7155 ± 97 signal events
Importance of $\gamma$ from $B \to DK$

- $\gamma$ plays a unique role in flavour physics
  - the only CP violating parameter that can be measured through tree decays

- A benchmark Standard Model reference point
  - doubly important after New Physics is observed

\[ \propto V_{cb} V_{us}^* \]

\[ \propto V_{ub} V_{cs}^* \]

Variants use different B or D decays
require a final state common to both $D^0$ and $\bar{D}^0$
Why is $B \to DK$ so nice?

- For theoretists:
  - theoretically clean: no penguins; factorisation works
  - all parameters can be determined from data

- For experimentalists:
  - many different observables (different final states)
  - all parameters can be determined from data
  - $\gamma \& \delta_B$ (weak & strong phase differences), $r_B$ (ratio of amplitudes)
B → DK methods

- Different D decay final states
  - CP eigenstates, e.g. $K^+K^-$ (GLW)
  - doubly-Cabibbo-suppressed decays, e.g. $K^+\pi^-$ (ADS)
  - singly-Cabibbo-suppressed decays, e.g., $K^{*+}K^-$ (GLS)
  - self-conjugate multibody decays, e.g., $K_S\pi^+\pi^-$ (GGSZ)

- Different B decays
  - never studied before (or not much)
  - $B^- \rightarrow DK^-, D^*K^-, DK^*$
  - $B^0 \rightarrow DK^{*0}$ (or $B \rightarrow DK\pi$ Dalitz plot analysis)
  - $B^0 \rightarrow DK_S$, $B^0_s \rightarrow D\phi$ (with or without time-dependence)
  - $B^0_s \rightarrow D^*_s K$, $B^0 \rightarrow D^{(*)}\pi$ (time-dependent)

Search for direct CP violation caused by $\gamma \neq 0$
All parameters from data – no theory input needed
Latest results on $B \rightarrow DK$ : GLW

Evidence for direct CP violation ($y \neq 0$)

$D_{CP} K A_{CP+}$

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Value ($y \neq 0$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BaBar</td>
<td>$0.25 \pm 0.06 \pm 0.02$</td>
</tr>
<tr>
<td>Belle</td>
<td>$0.29 \pm 0.06 \pm 0.02$</td>
</tr>
<tr>
<td>CDF</td>
<td>$0.39 \pm 0.17 \pm 0.04$</td>
</tr>
<tr>
<td>LHCb</td>
<td>$0.14 \pm 0.03 \pm 0.01$</td>
</tr>
<tr>
<td>Average HFAG</td>
<td>$0.19 \pm 0.03$</td>
</tr>
</tbody>
</table>

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Observed CP violation effects

As listed in PDG 2012

- **Kaon sector**
  - $|\epsilon| = (2.228 \pm 0.011) \times 10^{-3}$
  - $\text{Re}(\epsilon'/\epsilon) = (1.65 \pm 0.26) \times 10^{-3}$

- **B sector**
  - $S_{\psi K^0} = +0.679 \pm 0.020$
  - $S_{\eta' K^0} = +0.59 \pm 0.07$, $S_{\phi K^0} = +0.74^{+0.11}_{-0.13}$, $S_{f_0 K^0} = +0.69^{+0.10}_{-0.12}$, $S_{K^+ K^- K^0} = +0.68^{+0.09}_{-0.10}$
  - $S_{\pi^+ \pi^-} = -0.65 \pm 0.07$, $C_{\pi^+ \pi^-} = -0.36 \pm 0.06$
  - $S_{\psi \pi^0} = -0.93 \pm 0.15$, $S_{D^+ D^-} = -0.98 \pm 0.17$, $S_{D^{*+} D^{*-}} = -0.77 \pm 0.10$
  - $A_{K^+ \pi^\pm} = -0.087 \pm 0.008$
  - $A_{D^{(CP+)} K^\pm} = +0.19 \pm 0.03$

Only one in charged B mesons!
The other Unitarity Triangles

- High statistics available at LHCb will allow sensitivity to smaller CP violating effects
  - CP violating phase in $B_s$ oscillations ($O(\lambda^4)$)
    - $B_s$ oscillations ($\Delta m_s$) measured 2006 (CDF)
  - CP violating phase in $D^0$ oscillations ($O(\lambda^5)$)
    - $D^0$ oscillations ($\chi_D = \Delta m_D / \Gamma_D$ & $y_D = \Delta \Gamma_D / 2 \Gamma_D$) measured 2007 (Babar, Belle, later CDF)

- Observations of CP violation in both $K^0$ and $B^0$ systems won Nobel prizes!
Time-dependent CP Violation Formalism

- Generic (but shown for $B_s$) decays to CP eigenstates

\[
\Gamma( B_s(t) \rightarrow f ) = \mathcal{N}_f |A_f|^2 \frac{1 + |\lambda_f|^2}{2} e^{-\Gamma t} \times \left[ \cosh \frac{\Delta \Gamma t}{2} + A_{\text{dir}}^{\text{CP}} \cos(\Delta m t) + A_{\Delta \Gamma} \sinh \frac{\Delta \Gamma t}{2} + A_{\text{mix}}^{\text{CP}} \sin (\Delta m t) \right]
\]

\[
\Gamma( \overline{B}_s(t) \rightarrow f ) = \mathcal{N}_f |A_f|^2 \frac{1 + |\lambda_f|^2}{2} (1 + a) e^{-\Gamma t} \times \left[ \cosh \frac{\Delta \Gamma t}{2} - A_{\text{dir}}^{\text{CP}} \cos(\Delta m t) + A_{\Delta \Gamma} \sinh \frac{\Delta \Gamma t}{2} - A_{\text{mix}}^{\text{CP}} \sin(\Delta m t) \right].
\]
Time-dependent CP Violation Formalism

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\Gamma(B_s(t) \to f) = \mathcal{N}_f |A_f|^2 \frac{1+|\lambda_f|^2}{2} e^{-\Gamma t} \\
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\times \left[ \cosh \frac{\Delta \Gamma t}{2} - A_{\text{dir}}^{\text{CP}} \cos(\Delta m t) + A_{\Delta \Gamma} \sinh \frac{\Delta \Gamma t}{2} - A_{\text{mix}}^{\text{CP}} \sin(\Delta m t) \right].
\]

CP violating asymmetries

\[
A_{\text{dir}}^\text{CP} = C_{\text{CP}} = \frac{1-|\lambda_{\text{CP}}|^2}{1+|\lambda_{\text{CP}}|^2} \quad A_{\Delta \Gamma} = \frac{2 \Re(\lambda_{\text{CP}})}{1+|\lambda_{\text{CP}}|^2} \quad A_{\text{mix}}^\text{CP} = S_{\text{CP}} = \frac{2 \Im(\lambda_{\text{CP}})}{1+|\lambda_{\text{CP}}|^2}
\]

\[
(A_{\text{CP}}^{\text{dir}})^2 + (A_{\Delta \Gamma})^2 + (A_{\text{CP}}^{\text{mix}})^2 = 1
\]
Time-dependent CP Violation Formalism

- Generic (but shown for $B_s$) decays to CP eigenstates

$$\Gamma(B_s(t) \to f) = N_f |A_f|^2 \frac{1+|\lambda_f|^2}{2} e^{-\Gamma t}$$

$$\times \left[ \cosh \frac{\Delta \Gamma t}{2} + A_{\Delta \Gamma} \sinh \frac{\Delta \Gamma t}{2} \right]$$

$$\Gamma(\bar{B}_s(t) \to f) = N_f |A_f|^2 \frac{1+|\lambda_f|^2}{2} (1 + a) e^{-\Gamma t}$$

$$\times \left[ \cosh \frac{\Delta \Gamma t}{2} + A_{\Delta \Gamma} \sinh \frac{\Delta \Gamma t}{2} \right].$$

- Untagged analyses still sensitive to some interesting physics
Time-dependent CP Violation Formalism

- Generic (but shown for $B_s$) decays to CP eigenstates

\[
\Gamma(B_s(t) \rightarrow f) = \mathcal{N}_f |A_f|^2 \frac{1 + |\lambda_f|^2}{2} e^{-\Gamma t}
\]

\[
\times \left[ \cosh \frac{\Delta \Gamma t}{2} + 0 + A_{\Delta \Gamma} \sinh \frac{\Delta \Gamma t}{2} + A_{\text{CP}}^{\text{mix}} \sin(\Delta m t) \right]
\]

\[
\Gamma(\overline{B}_s(t) \rightarrow f) = \mathcal{N}_f |A_f|^2 \frac{1 + |\lambda_f|^2}{2} (1 + 0) e^{-\Gamma t}
\]

\[
\times \left[ \cosh \frac{\Delta \Gamma t}{2} - 0 + A_{\Delta \Gamma} \sinh \frac{\Delta \Gamma t}{2} - A_{\text{CP}}^{\text{mix}} \sin(\Delta m t) \right].
\]

- In some channels, expect no direct CP violation
- and/or no CP violation in mixing
Time-dependent CP Violation Formalism

- Generic (but shown for \( B_s \)) decays to CP eigenstates

\[
\Gamma(B_s(t) \rightarrow f) = \mathcal{N}_f |A_f|^2 \left(\frac{1 + |\lambda_f|^2}{2}\right) e^{-\Gamma t} \times \left[ 1 + A_{\text{CP}}^{\text{dir}} \cos(\Delta m t) + 0 + A_{\text{CP}}^{\text{mix}} \sin(\Delta m t) \right]
\]

\[
\Gamma(\overline{B}_s(t) \rightarrow f) = \mathcal{N}_f |A_f|^2 \left(\frac{1 + |\lambda_f|^2}{2}\right) (1 + a) e^{-\Gamma t} \times \left[ 1 - A_{\text{CP}}^{\text{dir}} \cos(\Delta m t) + 0 - A_{\text{CP}}^{\text{mix}} \sin(\Delta m t) \right].
\]

- In some channels, expect no direct CP violation
- \( B_d \) case: \( \Delta \Gamma \) negligible
Time-dependent CP Violation Formalism

- Generic (but shown for $B_s$) decays to CP eigenstates

$$\Gamma(B_s(t) \to f) = N_f |A_f|^2 \frac{1 + |\lambda_f|^2}{2} e^{-\Gamma t} \times \left[ 1 + A_{\Delta \Gamma} \frac{\Delta m}{\Gamma} \pm \frac{\Delta \Gamma}{2\Gamma} y \Gamma t + A_{\text{mix}}^{\text{CP}} \pm \frac{\Delta \Gamma}{2\Gamma} x \Gamma t \right]$$

$$\Gamma(\bar{B}_s(t) \to f) = N_f |A_f|^2 \frac{1 + |\lambda_f|^2}{2} (1 + a) e^{-\Gamma t} \times \left[ 1 - A_{\Delta \Gamma} \frac{\Delta m}{\Gamma} \pm \frac{\Delta \Gamma}{2\Gamma} y \Gamma t - A_{\text{mix}}^{\text{CP}} \pm \frac{\Delta \Gamma}{2\Gamma} x \Gamma t \right].$$

- In some channels, expect no direct CP violation

- $B_d$ case: $\Delta \Gamma$ negligible

- $D^0$ case: both $x = \Delta m/\Gamma$ and $y=\Delta \Gamma/2\Gamma$ small

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Flavour Physics
Charm mixing and CP violation

HFAG world average Including results from BABAR, Belle, CDF, CLEO(c), FOCUS

At LHCb can use $D \rightarrow K^+K^-$ to measure
- $A_{\Delta\Gamma} y_D$ (untagged or tagged); $A_{\text{mix}}^{\text{CP}} x_D$ (tagged)

Many other possible channels
Evidence for CP violation in $D \rightarrow h^+h^-$ decays

Measurement of CP asymmetry at pp collider requires knowledge of production and detection asymmetries; e.g. for $D^0 \rightarrow f$, where D meson flavour is tagged by $D^{*+} \rightarrow D^0 \pi^+$ decay

$$A_{raw}(f) = A_{CP}(f) + A_D(f) + A_D(\pi^+_s) + A_P(D^{*+})$$.

final state detection asymmetry vanishes for CP eigenstate

Cancel asymmetries by taking difference of raw asymmetries in two different final states (Since $A_D$ and $A_P$ depend on kinematics, must bin or reweight to ensure cancellation)

$$\Delta A_{CP} = A_{raw}(K^-K^+) - A_{raw}(\pi^-\pi^+)$$.
Evidence for CP violation in $D \to h^+h^-$ decays

Result, based on 0.62/fb of 2011 data

$\Delta A_{CP} = [-0.82 \pm 0.21\text{(stat.)} \pm 0.11\text{(syst.)}]\%$

$\Delta A_{CP}$ related mainly to direct CP violation
(contribution from indirect CPV suppressed by difference in mean decay time)

$\Delta A_{CP} \equiv A_{CP}(K^-K^+) - A_{CP}(\pi^-\pi^+)$

$= [a_{CP}^{\text{dir}}(K^-K^+) - a_{CP}^{\text{dir}}(\pi^-\pi^+)] + \frac{\Delta \langle t \rangle}{\tau} a_{CP}^{\text{ind}}$.
Evidence for CP violation in $D \to h^+h^-$ decays

- Naive SM expectation is for decays to be tree-dominated
  - Penguin contributions are possible for singly-Cabibbo-suppressed decays but CKM suppression is severe
  - So CP violation effects should be $O(10^{-4})$ … or should they?
    - Implications of the LHCb Evidence for Charm CP Violation arXiv:1111.4987
    - Direct CP violation in two-body hadronic charmed meson decays arXiv:1201.0785
    - CP asymmetries in singly-Cabibbo-suppressed $D$ decays to two pseudoscalar mesons arXiv:1201.2351
    - Direct CP violation in charm and flavor mixing beyond the SM arXiv:1201.6204
    - New Physics Models of Direct CP Violation in Charm Decays arXiv:1202.2866
    - Repercussions of Flavour Symmetry Breaking on CP Violation in D-Meson Decays arXiv:1202.3795
    - On the Universality of CP Violation in Delta $F = 1$ Processes arXiv:1202.5038
    - The Standard Model confronts CP violation in $D_0 \to \pi^+\pi^-$ and $D_0 \to K+K-$ arXiv:1203.3131
    - A consistent picture for large penguins in $D \to p_i+p_i^-, K+K-$ arXiv:1203.6659

... and many others! Further experimental input needed to clarify whether CPV is SM or NP
\[ \Phi_s = -2\beta_s (B_s \to J/\psi \phi) \]

- **VV final state**
  - three helicity amplitudes
  - → mixture of CP-even and CP-odd
    - disentangled using angular & time-dependent distributions
    - → additional sensitivity
  - many correlated variables
    - → complicated analysis
- **LHCb also uses** \( B_s \to J/\psi f_0 (f_0 \to \pi^+\pi^-) \)
  - CP eigenstate; simpler analysis
  - fewer events; requires input from \( J/\psi \phi \) analysis \((\Gamma_s, \Delta\Gamma_s)\)

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$B_s \rightarrow J/\psi\phi$ formalism

$A_0(0) \rightarrow$ CP even
$A_\parallel(0) \rightarrow$ CP even
$A_\perp(0) \rightarrow$ CP odd

± signs differ for $B_s$ and $\bar{B}_s$
CP violation in $B_s \to J/\psi\phi$ & $J/\psi\pi\pi$

LHCb-PAPER-2011-028
0.37/fb
LHCb-CONF-2012-002
LHCb-PAPER-2012-005
LHCb-PAPER-2012-006
All 1/fb

$\phi_s = -0.001 \pm 0.101$ (stat) $\pm 0.027$ (syst) rad,
$\Gamma_s = 0.6580 \pm 0.0054$ (stat) $\pm 0.0066$ (syst) ps$^{-1}$,
$\Delta\Gamma_s = 0.116 \pm 0.018$ (stat) $\pm 0.006$ (syst) ps$^{-1}$. 

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CP violation in $B_s \rightarrow J/\psi\phi$ & $J/\psi\pi\pi$

- Ambiguity resolution
- Tagged time-dependent angular analysis of $J/\psi\phi$ with $1/\text{fb}$
- Amplitude analysis to determine CP content of $J/\psi\pi\pi$
- Tagged time-dependent analysis of $J/\psi\pi\pi$

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Rare Decays
b → sγ rate and photon energy spectrum

Archetypal FCNC probe for new physics

\[ B(B \to X_s \gamma)_{E_\gamma > 1.7 \text{ GeV}} = (3.45 \pm 0.15 \pm 0.40) \times 10^{-4} \]

consistent with the SM prediction
b → sy photon polarisation measurement

- Search for time-dependent asymmetry
- Observable effect requires NP: left-handed current & new CP phase

\[ K^* \gamma S_{CP} vs C_{CP} \]

Excellent prospects for LHCb with \( B_s \to \phi \gamma \)

LHCb arXiv:1202.6267

Can also use, eg., \( B \to K^* e^+ e^- \) (low \( q^2 \))
\( B \rightarrow K^*\mu^+\mu^- \)

- \( b \rightarrow s l^+ l^- \) processes also governed by FCNCs
  - rates and asymmetries of many exclusive processes sensitive to NP
- Queen among them is \( B_d \rightarrow K^{*0}\mu^+\mu^- \)
  - superb laboratory for NP tests
  - experimentally clean signature
  - many kinematic variables …
  - … with clean theoretical predictions (at least at low \( q^2 \))
Operator Product Expansion

Build an effective theory for b physics
- take the weak part of the SM
- integrate out the heavy fields (W,Z,t)
- (like a modern version of Fermi theory for weak interactions)

\[ \mathcal{L}_{\text{full EW\times QCD}} \longrightarrow \mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{QED\times QCD}} \left( \text{quarks } \neq t \quad \& \text{leptons} \right) + \sum_n C_n(\mu) Q_n \]

- \( Q_n \) – local interaction terms (operators), \( C_n \) – coupling constants (Wilson coefficients)

Wilson coefficients
- encode information on the weak scale
- are calculable and known in the SM (at least to leading order)
- are affected by new physics

For \( K^*\mu\mu \) we care about \( C_7 \) (also affects \( b \rightarrow s\gamma \)), \( C_9 \) and \( C_{10} \)
Effective operators

\[ \mathcal{H}_{\Delta B = 1, \Delta C = 0, \Delta S = -1} = 4 \frac{G_F}{\sqrt{2}} \left( \lambda_c^8 (C_1(\mu)Q_1^c(\mu) + C_2(\mu)Q_2^c(\mu)) + \lambda_u^8 (C_1(\mu)Q_1^u(\mu) + C_2(\mu)Q_2^u(\mu)) - \sum_{i=3}^{10} \lambda_i^s C_i(\mu)Q_i(\mu) \right) \]

where the \( \lambda_q^s = V_{qb}^* V_{qs} \) and the operator basis is given by

- \( Q_1^q = \bar{b}_L^\alpha \gamma^\mu q_L^\alpha \bar{q}_L^\beta \gamma_\mu s_L^\beta \)
- \( Q_2^q = \bar{b}_L^\alpha \gamma^\mu q_L^\alpha \bar{q}_L^\beta \gamma_\mu s_L^\beta \)
- \( Q_3 = \bar{b}_L^\alpha \gamma^\mu s_L^\alpha \sum_q \bar{q}_L^\beta \gamma_\mu q_L^\beta \)
- \( Q_4 = \bar{b}_L^\alpha \gamma^\mu s_L^\alpha \sum_q \bar{q}_L^\beta \gamma_\mu q_L^\beta \)
- \( Q_5 = \bar{b}_L^\alpha \gamma^\mu s_L^\alpha \sum_q \bar{q}_R^\beta \gamma_\mu q_R^\beta \)
- \( Q_6 = \bar{b}_L^\alpha \gamma^\mu s_L^\alpha \sum_q \bar{q}_R^\beta \gamma_\mu q_R^\beta \)
- \( Q_7 = \frac{3}{2} \bar{b}_L^\alpha \gamma^\mu s_L^\alpha \sum_q e_q \bar{q}_R^\beta \gamma_\mu q_R^\beta \)
- \( Q_8 = \frac{3}{2} \bar{b}_L^\alpha \gamma^\mu s_L^\alpha \sum_q e_q \bar{q}_R^\beta \gamma_\mu q_R^\beta \)
- \( Q_9 = \frac{3}{2} \bar{b}_L^\alpha \gamma^\mu s_L^\alpha \sum_q e_q \bar{q}_L^\beta \gamma_\mu q_L^\beta \)
- \( Q_{10} = \frac{3}{2} \bar{b}_L^\alpha \gamma^\mu s_L^\alpha \sum_q e_q \bar{q}_L^\beta \gamma_\mu q_L^\beta \)

Four-fermion operators (except \( Q_{7\gamma} \) & \( Q_{8g} \)) – dimension 6
Theory of $B \to K^* \mu^+ \mu^-$

- Given for inclusive $b \to s \mu^+ \mu^-$ for simplicity
  - physics of exclusive modes $\approx$ same but equations are more complicated (involving form factors, etc.)

- Differential decay distribution

\[
\frac{d^2 \Gamma}{dq^2 \, d \cos \theta_l} = \frac{3}{8} \left[ (1 + \cos^2 \theta_l) H_T(q^2) + 2 \cos \theta_l H_A(q^2) + 2 (1 - \cos^2 \theta_l) H_L(q^2) \right]
\]

\[
H_T(q^2) \propto 2q^2 \left[ \left( C_9 + 2C_7 \frac{m_b^2}{q^2} \right)^2 + C_{10}^2 \right],
\]

\[
H_A(q^2) \propto -4q^2 C_{10} \left( C_9 + 2C_7 \frac{m_b^2}{q^2} \right),
\]

\[
H_L(q^2) \propto \left[ (C_9 + 2C_7)^2 + C_{10}^2 \right].
\]

This term gives a forward-backward asymmetry
Differential branching fraction and angular analysis of the $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ decay

LHCb-CONF-2012-008

Tim Gershon
Flavour Physics
Differential branching fraction
and angular analysis of the
$B^0 \rightarrow K^{*0} \mu^+ \mu^-$ decay

First measurement of the zero-crossing point of the forward-backward asymmetry
$q^2_0 = (4.9^{+1.1}_{-1.3})$ GeV$^2$

(SM predictions in the range $4.0 - 4.3$ GeV$^2$)

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

Killer app. for new physics discovery

- Very small in the SM
- Huge NP enhancement
  $(\tan \beta = \text{ratio of Higgs vevs})$
- Clean experimental signature

$$BR(B_s \rightarrow \mu^+\mu^-)^{SM} = (3.3 \pm 0.3) \times 10^{-8} \quad BR(B_s \rightarrow \mu^+\mu^-)^{MSSM} \propto \tan^6 \beta / M_{A0}^4$$
Latest results on $B_s \rightarrow \mu^+\mu^-$

**ATLAS (2.4/fb) arXiv:1204.0735**

**CMS (5/fb) arXiv:1203.3976**

$\text{ATLAS } B(B_s \rightarrow \mu^+\mu^-) < 2.2 \ (1.9) \times 10^{-8} @ 95\% \ (90\%) \ CL$

$\text{CMS } B(B_s \rightarrow \mu^+\mu^-) < 7.7 \ (6.4) \times 10^{-9} @ 95\% \ (90\%) \ CL$
Latest results on $B_s \rightarrow \mu^+\mu^-$

<table>
<thead>
<tr>
<th>Mode</th>
<th>Limit at 90% CL</th>
<th>Limit at 95% CL</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_s^0 \rightarrow \mu^+\mu^-$</td>
<td>Exp. bkg+SM $6.3 \times 10^{-9}$</td>
<td>$7.2 \times 10^{-9}$</td>
</tr>
<tr>
<td></td>
<td>Exp. bkg</td>
<td>$2.8 \times 10^{-9}$</td>
</tr>
<tr>
<td></td>
<td>Observed</td>
<td>$3.8 \times 10^{-9}$</td>
</tr>
<tr>
<td>$B^0 \rightarrow \mu^+\mu^-$</td>
<td>Exp. bkg</td>
<td>$0.91 \times 10^{-9}$</td>
</tr>
<tr>
<td></td>
<td>Observed</td>
<td>$0.81 \times 10^{-9}$</td>
</tr>
</tbody>
</table>

Standard Model expectation, e.g. $(3.2 \pm 0.2) \times 10^{-9}$

Buras, arXiv:1012.1447

Why does LHCb get a better limit than ATLAS/CMS?
Implications

G. Dissertori at Moriond QCD summary talk:
“Numbers most often mentioned: $3.2 \times 10^{-9}$ and 125”

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N. Mahmoudi at Moriond
Implications

G. Dissertori Moriond QCD summary talk:
“Numbers most often mentioned: $3.2 \times 10^{-9}$ and 125”

“the wow plot”

Simple TeV-scale models with large $\tan \beta$ ~ ruled out

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N. Mahmoudi at Moriond
LHCb upgrade

• To fully exploit LHC potential for heavy flavour physics will require an upgrade to LHCb
  – full readout & trigger at 40 MHz to enable high L running
  – “high L” = $10^{33}$/cm$^2$/s (so independent of machine upgrade)
  – planned for 2018 shutdown

• Physics case:
  – “exploration” of 1$^\text{st}$ phase will become “precision studies”
  – new opportunities for exploration open up (e.g. testing consistency of CP violation in tree vs. loop processes)
What is the LHC era?

Probably already out-of-date

update of European HEP Roadmap

LHCb upgrade

... it is the foreseeable future!
Other future flavour experiments

- SuperKEKB/Belle2 & SuperB
  - $B \to \tau \nu$, inclusive measurements, $\tau$ physics, ...

- Rare kaon decays
  - $K^+ \to \pi^+ \nu \nu$ (NA62, CERN); $K^0 \to \pi^0 \nu \nu$ (K0T0, J-PARC)

- Muon to electron conversion (charged lepton flavour violation)
  - COMET/PRIME (J-PARC); mu2e (FNAL)
B → τν and charged Higgs limits

- Pure leptonic decays of charged B mesons very clean
  - clean SM prediction
  - clean effect of charged Higgs (2HDM or SUSY)

\[
BR(B^+ \rightarrow l^+ \nu)^{SM} = \frac{G_F m_B}{8 \pi} m_l^2 \left( 1 - \frac{m_l^2}{m_B^2} \right)^2 f_B^2 |V_{ub}|^2 \tau_B
\]

\[
BR(B^+ \rightarrow l^+ \nu)^{NP} = BR(B^+ \rightarrow l^+ \nu)^{SM} \left( 1 - \frac{m_B^2}{m_H^2} \tan^2 \beta \right)^2
\]

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Belle PRD 82 (2010) 071101
The holy grail of kaon physics: $K \to \pi \nu \nu$

Next generation experiments should measure these decays for the 1st time

- $K^+ \to \pi^+ \nu \nu$ (NA62, CERN)
- $K^0 \to \pi^0 \nu \nu$ (K0T0, J-PARC)
- Proposals also at FNAL
Future projects

- Nuclear transitions
- Pion decays
- Kaons
- Hyperon decays
- Tau decays
- Neutrino interactions
- Charm
- Bottom
- Dispersion relations
- Hadronic matrix elements
- Chiral perturbation theory
- Lattice QCD
- Great progress in theory anticipated
- Perturbative QCD
- Operator product expansion
- W decays
- CDF, D0, ATLAS, CMS
- Top
- BABAR, BELLE, LHCb
- Belle-2, SuperB, LHCb upgrade
- Project X
- KLOE-2, NA62, KOTO
- NA48, KTeV, PEP-III/PETA
- KEDR, FOCUS, CLEO, BES
- CHORUS
- Great progress in theory anticipated
Summary

- We still don't know:
  - why there are so many fermions in the SM
  - what causes the baryon asymmetry of the Universe
  - where exactly the new physics is ...
  - ... and what it's flavour structure is

- Prospects are good for progress in the next few years

- We need a continuing programme of flavour physics into the 2020s
  - complementary to the high-$p_T$ programme of the LHC
References and background reading

- Reviews by the Particle Data Group
  - http://pdg.lbl.gov/
- Heavy Flavour Averaging Group (HFAG)
  - http://www.slac.stanford.edu/xorg/hfag/
- CKMfitter & UTfit
- Review journals (e.g. Ann. Rev. Nucl. Part. Phys.)
  - http://nucl.annualreviews.org
- Proceedings of CKM workshops
- Books
  - CP violation, I.I.Bigi and A.I.Sanda (CUP)
  - CP violation, G.C.Branco, L.Lavoura & J.P.Silva (OUP)