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  – Why is flavour physics interesting?
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  – 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)
CP violation in decay

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

\[
A = |T|e^{i(\delta_T - \phi_T)} + |P|e^{i(\delta_P - \phi_P)} \\
\overline{A} = |T|e^{i(\delta_T + \phi_T)} + |P|e^{i(\delta_P + \phi_P)} \\
A_{CP} = \frac{\overline{A}^2 - A^2}{\overline{A}^2 + A^2} = \frac{2|T||P|\sin(\delta_T - \delta_P)\sin(\phi_T - \phi_P)}{|T|^2 + |P|^2 + 2|T||P|\cos(\delta_T - \delta_P)\cos(\phi_T - \phi_P)}
\]

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.”
The famous penguin story

**Penguin diagram**

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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 Murray Gell-Mann in 1991 and 1994 by the CLEO collaboration.

**Origin of the name**

John Ellis was the first to refer to a certain shape, and in part to a legendary bar-room conversation:

"Mary K. [Gaillard], Dimitri [Nefedov] and I were working on penguin diagrams while we were at the DESY conference in 1977. We debated the penguin name came in 1977.

In the spring of 1977, Mike and I thought the b quark mass before it was found. My student at CERN, Melissa Freier, and I, and Serge went to a party. I lost the word penguin at the end, and was replaced by "penguin" due to 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."
Direct CP asymmetries in charmless hadronic B decays

Tim Gershon
Flavour Physics
Direct CP violation in $B \to K\pi$

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

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

“Kπ puzzle”

Could be a sign of new physics …

... first need to rule out possibility of larger than expected QCD corrections
Clean observables in $B \to K\pi$ (etc.)

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

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)
$B^0 \rightarrow \pi^+\pi^- \& B^0_s \rightarrow K^+K^-$

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

JHEP 10 (2013) 183

Tim Gershon
Flavour Physics
Latest results on multibody charmless B decays

Large CP violation effects with strong variation across the Dalitz plot. Detailed studies will be necessary to understand origin of these effects.
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 $B \rightarrow DK$ so nice?

- **For theorists:**
  - 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
  - $B^- \rightarrow DK^-, D^*K^-, DK^*$
  - $B^0 \rightarrow DK^{*0}$ (or $B \rightarrow DK\pi$ Dalitz plot analysis)
  - $B^0 \rightarrow DK_S$, $B_s^0 \rightarrow D\phi$ (with or without time-dependence)
  - $B_s^0 \rightarrow D_s K$, $B^0 \rightarrow D^{(*)}\pi$ (time-dependent)

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

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

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

<table>
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<th>Experiment</th>
<th>Reference</th>
<th>Value</th>
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<td>BaBar</td>
<td>PRD 82 (2010) 072004</td>
<td>$0.25 \pm 0.06 \pm 0.02$</td>
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<tr>
<td>Belle</td>
<td>LP 2011 preliminary</td>
<td>$0.29 \pm 0.06 \pm 0.02$</td>
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<tr>
<td>CDF</td>
<td>PRD 81 (2010) 031105(R)</td>
<td>$0.39 \pm 0.17 \pm 0.04$</td>
</tr>
<tr>
<td>LHCb</td>
<td>PLB 712 (2012) 203</td>
<td>$0.14 \pm 0.03 \pm 0.01$</td>
</tr>
<tr>
<td>Average HFAG</td>
<td></td>
<td>$0.19 \pm 0.03$</td>
</tr>
</tbody>
</table>

PLB 712 (2012) 203
Observed CP violation effects

As listed in PDG 2014

• 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
  - $S_{\psi K^0} = +0.682 \pm 0.019$
  - $S_{\eta' K^0} = +0.63 \pm 0.06$, $S_{\phi K^0} = +0.74^{+0.11}_{-0.13}$, $S_{\eta' K^0} = +0.69^{+0.10}_{-0.12'}$, $S_{K^+ K^- K^0} = +0.68^{+0.09}_{-0.10}$
  - $S_{\pi^+ \pi^-} = -0.66 \pm 0.06$, $C_{\pi^+ \pi^-} = -0.31 \pm 0.05$
  - $S_{\psi \pi^0} = -0.93 \pm 0.15$, $S_{D^+ D^-} = -0.98 \pm 0.17$, $S_{D^{*+} D^{*-}} = -0.71 \pm 0.09$
  - $A_{K^+ \pi^\pm} = -0.082 \pm 0.006$, $A_{B_s \to K^+ \pi^\pm} = -0.082 \pm 0.006$
  - $A_{D(CP^+)K^\pm} = +0.19 \pm 0.03$, CP violation in the phase space of $B \to 3h$ decays
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 ($x_D = \Delta m_D/\Gamma_D$ & $y_D = \Delta \Gamma_D/2\Gamma_D$) 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

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

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

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

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

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

$$\Gamma(\overline{B_s}(t) \to f) = \mathcal{N}_f |A_f|^2 \frac{1 + |\lambda_f|^2}{2} (1 + a) e^{-\Gamma t}$$

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

CP violating asymmetries

CP conserving parameter

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

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

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

\[
\Gamma(B_s(t) \to f) = \mathcal{N}_f |A_f|^2 \frac{1 + |\lambda_f|^2}{2} e^{-\Gamma t} \\
\times \left[ \cosh \frac{\Delta \Gamma t}{2} + \mathcal{A}_{\Delta \Gamma} \sinh \frac{\Delta \Gamma t}{2} \right]
\]

\[
\Gamma(\bar{B}_s(t) \to f) = \mathcal{N}_f |A_f|^2 \frac{1 + |\lambda_f|^2}{2} (1 + a) e^{-\Gamma t} \\
\times \left[ \cosh \frac{\Delta \Gamma t}{2} + \mathcal{A}_{\Delta \Gamma} \sinh \frac{\Delta \Gamma t}{2} \right].
\]

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

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

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

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

$$\Gamma(\overline{B}_s(t) \to f) = N_f |A_f|^2 \frac{1 + |\lambda_f|^2}{2} (1 + 0) e^{-\Gamma t}$$

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

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

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

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

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

- In some channels, expect no CP violation in decay
- $B_d$ case: $\Delta \Gamma$ negligible
Time-dependent CP Violation Formalism

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

\[
\Gamma(B_s(t) \to f) = \mathcal{N}_f |A_f|^2 \frac{1 + |\lambda_f|^2}{2} e^{-\Gamma t} \times [1 + \mathcal{A}_{\text{dir}}^{\text{CP}} e^{\mathcal{A}_{\Delta \Gamma} t} + \mathcal{A}_{\Delta \Gamma} t + \mathcal{A}_{\text{mix}}^{\text{CP}} s \mathcal{X} \mathcal{X} \Gamma t]
\]

\[
\Gamma(\overline{B}_s(t) \to f) = \mathcal{N}_f |A_f|^2 \frac{1 + |\lambda_f|^2}{2} (1 + a) e^{-\Gamma t} \times [1 - \mathcal{A}_{\text{dir}}^{\text{CP}} e^{\mathcal{A}_{\Delta \Gamma} t} + \mathcal{A}_{\Delta \Gamma} t - \mathcal{A}_{\text{mix}}^{\text{CP}} s \mathcal{X} \mathcal{X} \Gamma t].
\]

- In some channels, expect no CP violation in decay

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

- $D^0$ case: both $x = \Delta m/\Gamma$ and $y=\Delta \Gamma/2\Gamma$ small
Charm mixing and CP violation
HFAG world average Including results from BABAR, Belle, CDF, CLEO(c), FOCUS, LHCb

Inconsistent with no mixing point (0,0)  Consistent with no CP violation point (1,0)

Tim Gershon
Flavour Physics
CP violation in D decay?

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

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

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)

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

\[ \Delta A_{CP} \equiv A_{CP}(K^- K^+) - A_{CP}(\pi^- \pi^+) = \left[ a_{CP}^{\text{dir}}(K^- K^+) - a_{CP}^{\text{dir}}(\pi^- \pi^+) \right] + \frac{\Delta \langle t \rangle}{\tau} a_{CP}^{\text{ind}}. \]

Singly Cabibbo-suppressed decays have tree and penguin contributions

Two body decays give largest yields – best sensitivity

Small contribution from “indirect” CP asymmetry due to non-perfect cancellation of decay time acceptance – also measured with decay-time-dependent methods
\[ \Phi_s = -2\beta_s (B_s \rightarrow J/\psi \phi) \]

- **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** \( B_s \rightarrow J/\psi f_0 \) \( (f_0 \rightarrow \pi^+\pi^-) \)
  - 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

Differential decay rate:

$\frac{d^4 \Gamma(B_s^0 \rightarrow J/\psi \phi)}{dt \, d\cos \theta \, d\phi \, d\cos \psi} = \frac{d^4 \Gamma}{dt \, d\Omega} \propto \sum_{k=1}^6 h_k(t) f_k(\theta, \psi, \phi)$

<table>
<thead>
<tr>
<th>$k$</th>
<th>$h_k(t)$</th>
<th>$h_{\bar{k}}(t)$</th>
<th>$f_k(\theta, \psi, \phi)$</th>
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<tr>
<td>1</td>
<td>$</td>
<td>A_0(0)</td>
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</tr>
<tr>
<td>2</td>
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<td>A_\parallel(0)</td>
<td>^2$</td>
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<tr>
<td>3</td>
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<td>A_\perp(0)</td>
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<td>4</td>
<td>$\Im {A_\parallel(0)A_\perp(0)}$</td>
<td>$\Im {A_\parallel(0)A_\perp(0)}$</td>
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<tr>
<td>5</td>
<td>$\Re {A_\parallel(0)A_\parallel(0)}$</td>
<td>$\Re {A_\parallel(0)A_\parallel(0)}$</td>
<td>$\frac{1}{\sqrt{2}} \sin 2\theta \sin^2 \theta \sin 2\phi$</td>
</tr>
<tr>
<td>6</td>
<td>$\Im {A_\parallel(0)A_\parallel(0)}$</td>
<td>$\Im {A_\parallel(0)A_\parallel(0)}$</td>
<td>$\frac{1}{\sqrt{2}} \sin 2\theta \sin 2\phi \cos \phi$</td>
</tr>
</tbody>
</table>

$\pm$ signs differ for $B_s$ and $\bar{B}_s$

\[ |\tilde{A}_0(t)|^2 = \tilde{A}_0(0)^2 e^{-\Gamma_s t} \left[ \cosh \left( \frac{\Delta \Gamma_s t}{2} \right) - \cos \Phi \sinh \left( \frac{\Delta \Gamma_s t}{2} \right) \right] \sin \Phi \sin (\Delta \kappa_s t), \]
\[ |\tilde{A}_\parallel(t)|^2 = \tilde{A}_\parallel(0)^2 e^{-\Gamma_s t} \left[ \cosh \left( \frac{\Delta \Gamma_s t}{2} \right) - \cos \Phi \sinh \left( \frac{\Delta \Gamma_s t}{2} \right) \right] \sin \Phi \sin (\Delta \kappa_s t), \]
\[ |\tilde{A}_\perp(t)|^2 = \tilde{A}_\perp(0)^2 e^{-\Gamma_s t} \left[ \cosh \left( \frac{\Delta \Gamma_s t}{2} \right) + \cos \Phi \sinh \left( \frac{\Delta \Gamma_s t}{2} \right) \right] + \sin \Phi \sin (\Delta \kappa_s t), \]
\[ \Im \{\tilde{A}_\parallel(t)\tilde{A}_\perp(t)\} = \tilde{A}_\parallel(0)\tilde{A}_\perp(0)e^{-\Gamma_s t} \left[ -\cos (\delta_\perp - \delta_\parallel) \sin \Phi \sinh \left( \frac{\Delta \Gamma_s t}{2} \right) \right], \]
\[ \Re \{\tilde{A}_\parallel(t)\tilde{A}_\parallel(t)\} = \tilde{A}_\parallel(0)\tilde{A}_\parallel(0)e^{-\Gamma_s t} \cos \delta_\parallel \left[ \cosh \left( \frac{\Delta \Gamma_s t}{2} \right) - \cos \Phi \sinh \left( \frac{\Delta \Gamma_s t}{2} \right) \right], \]
\[ \Im \{\tilde{A}_\parallel(0)\tilde{A}_\parallel(0)\} = \tilde{A}_\parallel(0)\tilde{A}_\parallel(0)e^{-\Gamma_s t} \right[ -\cos \delta_\parallel \sin \Phi \sinh \left( \frac{\Delta \Gamma_s t}{2} \right) \right], \]
\[ \Im \{\tilde{A}_0(t)\tilde{A}_\perp(t)\} = \tilde{A}_0(0)\tilde{A}_\perp(0)e^{-\Gamma_s t} \left[ -\cos \delta_\parallel \sin \Phi \sinh \left( \frac{\Delta \Gamma_s t}{2} \right) \right], \]
\[ \Im \{\tilde{A}_\parallel(0)\tilde{A}_\parallel(0)\} = \tilde{A}_\parallel(0)\tilde{A}_\parallel(0)e^{-\Gamma_s t} \left[ -\cos \delta_\parallel \sin \Phi \sinh \left( \frac{\Delta \Gamma_s t}{2} \right) \right]. \]
CP violation in $B_c \rightarrow J/\psi \phi$ & $J/\psi \pi \pi$
CP violation in interference between $B_s$ mixing and $b \to \bar{c}c\bar{s}$ decay ($\phi_s$)
Rare Decays
\[ B_{(s)}^0 \rightarrow \mu^+\mu^- \]

**Killer app. for new physics discovery**

- **Very small in the SM**
  - no tree-level FCNC
  - CKM suppression
  - helicity suppression

- **Huge NP enhancement possible** (\( \tan \beta = \text{ratio of Higgs vevs} \))

  \[
  BR\left( B_s \rightarrow \mu^+\mu^- \right)^{SM} = (3.3 \pm 0.3) \times 10^{-9} \\
  BR\left( B_s \rightarrow \mu^+\mu^- \right)^{MSSM} \propto \tan^6 \beta / M_{A0}^4
  \]

- **Clean experimental signature**
$B_{(s)}^0 \rightarrow \mu^+\mu^-$

Searches over 30 years
$B_{(s)}^0 \rightarrow \mu^+\mu^-$ – analysis ingredients

- Produce a very large sample of B mesons
- Trigger efficiently on dimuon signatures
- Reject background
  - excellent vertex resolution (identify displaced vertex)
  - excellent mass resolution (identify B peak)
    - also essential to resolve $B^0$ from $B^0_s$ decays
  - powerful muon identification (reject background from B decays with misidentified pions)
  - typical to combine various discriminating variables into a multivariate classifier
    - e.g. Boosted Decision Trees algorithm
$B^{0}_{(s)} \rightarrow \mu^{+}\mu^{-}$

latest results from CMS & LHCb

CMS PRL 111 (2013) 101804

LHCb PRL 111 (2013) 101805

Events weighted by $S/(S+B)$

Only events with BDT > 0.7

Tim Gershon
Flavour Physics
Combination of CMS and LHCb data results in first observation of $B_s \rightarrow \mu^+ \mu^-$ and first evidence for $B^0 \rightarrow \mu^+ \mu^-$

Results consistent with SM at $2\sigma$ level
B → K*μ⁺μ⁻

- b → sl⁺l⁻ processes also governed by FCNCs
  - rates and asymmetries of many exclusive processes sensitive to NP

- Queen among them is $B_d \rightarrow K^{*0}μ^+μ^-$
  - 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)

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

- \( Q_n \) – 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

\[ \mathcal{H}_{WB}^{\Delta B=1, \Delta C=0, \Delta S=-1} = 4 \frac{G_F}{\sqrt{2}} \left( \lambda^s_c (C_1(\mu)Q_1^c(\mu) + C_2(\mu)Q_2^c(\mu)) ight) + \lambda^s_u (C_1(\mu)Q_1^u(\mu) + C_2(\mu)Q_2^u(\mu)) - \lambda^s_t \sum_{i=3}^{10} C_i(\mu)Q_i(\mu) \]

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

\[
\begin{align*}
Q_1 &= \bar{b}_L^\alpha \gamma^\mu q_L^\alpha \bar{q}_L^\beta \gamma^\mu s_L^\beta \\
Q_3 &= \bar{b}_L^\alpha \gamma^\mu s_L^\alpha \sum_q \bar{q}_L^\beta \gamma^\mu q_L^\beta \\
Q_5 &= \bar{b}_L^\alpha \gamma^\mu s_L^\alpha \sum_q \bar{q}_R^\beta \gamma^\mu q_R^\beta \\
Q_7 &= \frac{3}{2} \bar{b}_L^\alpha \gamma^\mu s_L^\alpha \sum_q e_q \bar{q}_R^\beta \gamma^\mu q_R^\beta \\
Q_9 &= \frac{3}{2} \bar{b}_L^\alpha \gamma^\mu s_L^\alpha \sum_q e_q \bar{q}_L^\beta \gamma^\mu q_L^\beta \\
Q_2 &= \bar{b}_L^\beta \gamma^\mu s_L^\alpha \bar{q}_L^\gamma \gamma^\mu s_L^\alpha \\
Q_4 &= \bar{b}_L^\beta \gamma^\mu s_L^\alpha \sum_q \bar{q}_L^\gamma \gamma^\mu q_L^\alpha \\
Q_6 &= \bar{b}_L^\beta \gamma^\mu s_L^\alpha \sum_q \bar{q}_R^\gamma \gamma^\mu q_R^\alpha \\
Q_8 &= \frac{3}{2} \bar{b}_L^\gamma \gamma^\mu s_L^\alpha \sum_q e_q \bar{q}_R^\gamma \gamma^\mu q_R^\alpha \\
Q_9 &= \frac{3}{2} \bar{b}_L^\gamma \gamma^\mu s_L^\alpha \sum_q e_q \bar{q}_L^\gamma \gamma^\mu q_L^\alpha \\
Q_{7\gamma} &= \frac{e}{16\pi^2} m_b \bar{b}_L^\alpha \sigma^{\mu\nu} F_{\mu\nu} s_L^\alpha \\
Q_{8g} &= \frac{g_8}{16\pi^2} m_b \bar{b}_L^\alpha \sigma^{\mu\nu} G_{\mu\nu}^A T^A s_L^\alpha \\
Q_{9V} &= \frac{1}{2} \bar{b}_L^\alpha \gamma^\mu s_L^\alpha \bar{q}_L^\gamma \gamma^\mu l \\
Q_{10A} &= \frac{1}{2} \bar{b}_L^\alpha \gamma^\mu s_L^\alpha \bar{q}_L^\gamma \gamma^\mu s_L^\gamma l
\end{align*}
\]

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

- Differential decay distribution

$$\frac{1}{d(G + \bar{G})/dq^2} \frac{d^3(G + \bar{G})}{d\Omega} \bigg|_P = \frac{9}{32\pi} \left[ \frac{3}{4}(1 - F_L) \sin^2 \theta_K + F_L \cos^2 \theta_K \right. \left. + \frac{1}{4}(1 - F_L) \sin^2 \theta_K \cos 2\theta_l - F_L \cos^2 \theta_K \cos 2\theta_l + S_3 \sin^2 \theta_K \sin^2 \theta_l \cos 2\phi \right. \left. + S_4 \sin 2\theta_K \sin 2\theta_l \cos \phi + S_5 \sin 2\theta_K \sin \theta_l \cos \phi \right. \left. + \frac{4}{3} A_{FB} \sin^2 \theta_K \cos \theta_l + S_7 \sin 2\theta_K \sin \theta_l \sin \phi \right. \left. + S_8 \sin 2\theta_K \sin 2\theta_l \sin \phi + S_9 \sin^2 \theta_K \sin^2 \theta_l \sin 2\phi \right].$$

$S_i$ terms related to Wilson coefficients and form factors

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Flavour Physics
Full angular analysis of $B^0 \rightarrow K^{*0} \mu^+ \mu^-$

- Example of fits, in $1.1 < q^2 < 6.0$ GeV$^2$ bin

Angle and $m(K\pi)$ projections in $\pm 50$ MeV around B peak
Full angular analysis of $B^0 \rightarrow K^{*0}\mu^+\mu^-$

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Flavour Physics
Full angular analysis of $B^0 \rightarrow K^{*0} \mu^+ \mu^-$
Tension in $P_{5}'$

- Dimuon pair is predominantly spin-1
  - either vector (V) or axial-vector (A)
- There are 6 non-negligible amplitudes
  - 3 for VV and 3 for VA
  - expressed as $A_{0,\perp,\parallel}^{L,R}$ (transversity basis)
- $P_{5}'$ related to difference between relative phase of longitudinal (0) and perpendicularly (⊥) polarised amplitudes for VV and VA
  - constructed so as to minimise form-factor uncertainties

$$P_{5}' = \sqrt{2} \frac{\text{Re} \left( A_0^L A_\perp^{L*} - A_0^R A_\perp^{R*} \right)}{\sqrt{(|A_0^L|^2 + |A_0^R|^2) \left(|A_\parallel^L|^2 + |A_\parallel^R|^2 + |A_\perp^L|^2 + |A_\perp^R|^2 \right)}}$$

Sensitive to NP in V or A couplings (Wilson coefficients $C_9^{(i)}$ & $C_{10}^{(i)}$)
$b \to s \mu^+ \mu^-$ branching fractions

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

LHCb

**$B^0 \to K^{*0} \mu^+ \mu^-$**

LHCb

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

LHCb

**$\Lambda_b \to \Lambda \mu^+ \mu^-$**

LHCb

Trend to be below SM prediction at low $q^2$?
Lepton universality – $R_K$

Deficit of $B \to K\mu^+\mu^-$ compared to expectation
also seen in $K\mu^+\mu^-/Ke^+e^-$ ratio ($R_K$) – negligible theoretical uncertainty

$R_K(1 < q^2 < 6 \text{ GeV}^2) = 0.745 \pm 0.036$

<3σ from SM but suggestive
B → D^{(*)}\tau\nu

- Powerful channel to test lepton universality
  - ratios \( R(D^{(*)}) = \frac{B(B \to D^{(*)}\tau\nu)}{B(B \to D^{(*)}\mu\nu)} \) could deviate from SM values, e.g. in models with charged Higgs
- Heightened interest in this area
  - anomalous results from BaBar
  - other hints of lepton universality violation, e.g. \( R_K \), \( H \to \tau\mu \)
B → D*τν at LHCb

- Identify B → D*τν, D* → Dπ, D → Kπ, τ → μνν
  - Kinematic reconstruction to calculate $M_{\text{miss}}^2 = (p_B - p_{D^*} - p_\mu)^2$
  - Require significant B, D, τ flight distance & use isolation MVA
- Separate signal / background by fitting in $M_{\text{miss}}^2$, $q^2$ and $E_\mu$
  - Shown below high $q^2$ region only (best sensitivity)

\[
R(D^*) = 0.336 \pm 0.027 \pm 0.030
\]

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Very preliminary & unofficial average including new LHCb & Belle results

Tension with SM seems to persist

\[ \Delta \chi^2 = 1.0 \]

\[ R(D^*) = 0.390 \pm 0.047 \]

\[ R(D) = 0.322 \pm 0.021 \]

Careful averaging needed to account for statistical and systematic correlations

SM predictions from PRD 85 (2012) 094025

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Thanks to M. Rotondo
Summary of rare decays

• Accumulating hints of non-SM effects?
  – in particular related to lepton universality
  – observables with negligible theoretical uncertainty

• It is easy to see patterns, yet there may be none
  – no single effect with 5σ significance
  – various models proposed that can explain effects

• Need more data!
  – many results still to come from Run I data
  – from ATLAS and CMS, as well as LHCb
  – … and Run II is happening
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)
LHC upgrade and the all important trigger

- Readout detector at 40 MHz
- Implement trigger fully in software → efficiency gains
- Run at $L_{\text{inst}}$ up to $2 \times 10^{33}/\text{cm}^2/\text{s}$

- Higher luminosity
  - Need to cut harder at L0 to keep rate at 1 MHz
  - Lower efficiency

- Software High Level Trigger
  - Introduce tracking/PID information, find displaced tracks/vertices
  - Offline reconstruction tuned to trigger time constraints
  - Mixture of exclusive and inclusive selection algorithms

- L0 Hardware Trigger
  - Readout, high $E_T/P_T$ signatures
  - 450 kHz h²
  - 400 kHz $\mu/\mu\mu$
  - 150 kHz e/γ

- 40 MHz bunch crossing rate

- Limitation is here

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Tim Gershon
Flavour Physics
LHC upgrade and the all important trigger

- 40 MHz bunch crossing rate
- L0 Hardware Trigger: 1 MHz readout, high $E_T/P_T$ signatures
  - 450 kHz $h^\pm$
  - 400 kHz $\mu/\mu\mu$
  - 150 kHz $e/\gamma$
- Software High Level Trigger
  - 29000 Logical CPU cores
  - Offline reconstruction tuned to trigger time constraints
  - Mixture of exclusive and inclusive selection algorithms
- 5 kHz Rate to storage
  - 2 kHz Inclusive Topological
  - 2 kHz Inclusive/Exclusive Charm
  - 1 kHz Muon and DiMuon

• readout detector at 40 MHz
• implement trigger fully in software → efficiency gains
• run at $L_{\text{inst}}$ up to $2 \times 10^{33}/\text{cm}^2/\text{s}$
LHCb detector upgrade

- **VELO**
  - Si strips
  - Replace all

- **Silicon Tracker**
  - Si strips
  - Replace all

- **Outer Tracker**
  - Straw tubes
  - Replace R/O

- **MUON**
  - Almost compatible

- **RICH**
  - HPDs
  - Replace HPD, R/O

- **Central Fiber Option**
  - Fibers
  - New design and R/O

- **Calo**
  - PMTs
  - Reduce PMT gain, Replace R/O
Other future flavour experiments

- **SuperKEKB/Belle2 & SuperB**
  - $B \rightarrow \tau \nu$, inclusive measurements, $\tau$ physics, …
- **Rare kaon decays**
  - $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ (NA62, CERN); $K^0 \rightarrow \pi^0 \nu \bar{\nu}$ (K0T0, J-PARC)
- **Muon to electron conversion (charged lepton flavour violation)**
  - COMET/PRIME (J-PARC); mu2e (FNAL)
The holy grail of kaon physics: $K \to \pi \nu \bar{\nu}$

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

- $K^+ \to \pi^+ \nu \bar{\nu}$ (NA62, CERN)
- $K^0 \to \pi^0 \nu \bar{\nu}$ (K0T0, J-PARC)
The need for more precision

• “Imagine if Fitch and Cronin had stopped at the 1% level, how much physics would have been missed”
  – A.Soni

• “A special search at Dubna was carried out by Okonov and his group. They did not find a single $K_L^0 \rightarrow \pi^+\pi^-$ event among 600 decays into charged particles (Anikira et al., JETP 1962). At that stage the search was terminated by the administration of the lab. The group was unlucky.”
  – L.Okun

(remember: $B(K_L^0 \rightarrow \pi^+\pi^-) \sim 2 \times 10^{-3}$)
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

• Will have continuing programme of flavour physics into the 2020s and perhaps beyond
  – 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)