Flavour Physics

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Outline

• Lecture 4
  – B physics
    • time-dependent CP violation
    • the B factories BaBar and Belle
    • measurements of UT angles $\beta$ and $\alpha$
    • the LHCb experiment (B physics at hadron machines)
    • searches for new physics in
      – $B_s$ oscillations
      – rare B decays
  – Future flavour physics
Some theory papers

- Ellis, Gaillard, Nanopoulos & Rudaz, NPB 131, 285 (1977)
- Bander, Silverman & Soni, PRL 43, 242 (1979)
  - CP violation may be large in the B system
  - time-dependence in $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B^0\overline{B}^0$
- Bigi & Sanda, NPB 193, 85 (1981)
  - $B^0 \rightarrow J/\psi K_S$ and other possible decay modes
Categories of CP violation

- Consider decay of neutral particle to a CP eigenstate

\[ \lambda_{CP} = \frac{q \bar{A}}{p A} \]

- CP violation in mixing
  \[ \left| \frac{q}{p} \right| \neq 1 \]

- CP violation in decay (direct CPV)
  \[ \left| \frac{\bar{A}}{A} \right| \neq 1 \]

- CP violation in interference between mixing and decay
  \[ \Im \left( \frac{q \bar{A}}{p A} \right) \neq 0 \]
Neutral B mixing parameters

- Recall: \( \frac{q}{p} = -\frac{(\Delta m - \frac{1}{2}i\Delta \Gamma)}{2(M_{12} - \frac{1}{2}i\Gamma_{12})} \)

\[
(\Delta m)^2 - \frac{1}{4}(\Delta \Gamma)^2 = 4(|M_{12}|^2 + \frac{1}{4}|\Gamma_{12}|^2) \quad \Delta m \Delta \Gamma = 4\text{Re}(M_{12} \Gamma_{12}^*)
\]

- In the neutral B system \( \Delta m >> \Delta \Gamma \)

\[
\Delta m \sim 2|M_{12}| \quad \Delta \Gamma \sim 2\text{Re}(M_{12} \Gamma_{12}^*)/|M_{12}| \quad \frac{q}{p} \sim -|M_{12}|/M_{12}
\]

- \( |M_{12}| \) from mixing diagram

\[
\Rightarrow \frac{q}{p} \sim e^{-2i\beta} \text{ (in the usual phase convention)}
\]
Evolution with time

• Consider a $B$ meson which is known to be $B^0$ at time $t=0$

• At later time $t$:

\[ B^0_{(\text{phys})}(\Delta t) = e^{-iM_{B^0}t} e^{-\Gamma t/2} \cos(\Delta m \Delta t/2) B^0 + i \frac{q}{p} e^{-iM_{B^0}t} e^{-\Gamma t/2} \sin(\Delta m \Delta t/2) B^0 \]

• Similarly

\[ B^0_{(\text{phys})}(\Delta t) = \left( \frac{p}{q} \right) i e^{-iM_{B^0}t} e^{-\Gamma t/2} \sin(\Delta m \Delta t/2) B^0 + e^{-iM_{B^0}t} e^{-\Gamma t/2} \cos(\Delta m \Delta t/2) B^0 \]
Time-Dependent CP Violation in the $B^0 - \overline{B}^0$ System

- For a $B$ meson known to be 1) $B^0$ or 2) $\overline{B}^0$ at time $t=0$, that at later time $t$ decays to the CP eigenstate $f_{CP}$:

$$
\Gamma (B^0_{phys} \to f_{CP}(t)) \propto e^{-\Gamma t} \left( 1 - (S \sin(\Delta m t) - C \cos(\Delta m t)) \right)
$$

$$
\Gamma (\overline{B}^0_{phys} \to f_{CP}(t)) \propto e^{-\Gamma t} \left( 1 + (S \sin(\Delta m t) - C \cos(\Delta m t)) \right)
$$

Here assume $\Delta \Gamma$ negligible – will see full expressions later.

$$
S = \frac{2 \Im(\lambda_{CP})}{1 + \left| \lambda_{CP}^2 \right|} \quad C = \frac{1 - \left| \lambda_{CP}^2 \right|}{1 + \left| \lambda_{CP}^2 \right|} \quad \lambda_{CP} = \frac{q}{p A}
$$

For $B^0 \to J/\psi K_S$, $S = \sin(2\beta)$, $C=0$

NPB 193 (1981) 85
The golden mode – $B^0 \rightarrow J/\psi \; K_S$

- Dominated by $b \rightarrow c\bar{c}s$ tree diagram
  - subleading $b \rightarrow scc\bar{c}$ penguin has (predominantly) the same weak phase

- $|A| = |A| \Rightarrow$ no direct CP violation

- $C = 0$ & $S = -\eta_{CP} \sin(2\beta)$

- Reasonable branching fraction & experimentally clean signature
Problem

• How can we measure decay time in $e^+e^- \rightarrow Y(4S) \rightarrow B^0\bar{B}^0$?

• The answer: (P. Oddone)

  asymmetric-energy B factory

• Key points
  – $Y(4S) \rightarrow B^0\bar{B}^0$ produces coherent pairs
  – B mesons are moving in lab frame
Asymmetric B factory principle

KEKB energies

$\tau$ (4S) resonance

$B_1$ and $B_2$

$t=0$ and $t=t$

$B^0$ and $\bar{B}^0$

$V_\mu$

$\mu^+$, $J/\Psi$

$\mu^-$

$K_s$

$\pi^+$, $\pi^-$

$\Delta Z \sim 200 \mu m$
Asymmetric B Factories

PEPII at SLAC
9.0 GeV e\(^-\) on 3.1 GeV e\(^+\)

KEKB at KEK
8.0 GeV e\(^-\) on 3.5 GeV e\(^+\)
B factories – world record luminosities

~ 433/fb on $\Upsilon(4S)$

~ 711/fb on $\Upsilon(4S)$
Belle Detector

SC solenoid
1.5T

CsI(Tl)
16X₀

TOF counter

Aerogel Cherenkov cnt.
n=1.015~1.030

Central Drift Chamber
small cell +He/C₂H₆

Si vtx. det.
- 3 lyr. DSSD
- 4 lyr. since summer 2003

μ / K_L detection
14/15 lyr. RPC+Fe

8 GeV e⁻

3.5 GeV e^+

Belle Detector
BaBar Detector

- DIRC (PID)
  - 144 quartz bars
  - 11000 PMs

- 1.5 T solenoid

- EMC
  - 6580 CsI(Tl) crystals

- Drift Chamber
  - 40 stereo layers

- Instrumented Flux Return
  - iron / RPCs (muon / neutral hadrons)
  - 2/6 replaced by LST in 2004
  - Rest of replacement in 2006

- $e^+ (3.1 \text{ GeV})$

- $e^- (9 \text{ GeV})$

- Silicon Vertex Tracker
  - 5 layers, double sided strips
Results for the golden mode

$B^0 \rightarrow J/\psi K^0$

$\eta_f = -1$

$\eta_f = +1$

PRD 79 (2009) 072009

PRL 108 (2012) 171802
Compilation of results

\[ \sin(2\beta) \equiv \sin(2\phi_1) \]

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Date</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>BaBar</td>
<td>PRD 79 (2009)</td>
<td>0.69 ± 0.03 ± 0.01</td>
</tr>
<tr>
<td>BaBar ( \chi_0^0 ) ( K_S )</td>
<td>PRD 80 (2009)</td>
<td>0.69 ± 0.52 ± 0.04 ± 0.07</td>
</tr>
<tr>
<td>BaBar ( J/\psi ) (hadronic) ( K_S )</td>
<td>PRD 69 (2004)</td>
<td>1.56 ± 0.42 ± 0.21</td>
</tr>
<tr>
<td>Belle</td>
<td>PRL 108 (2012)</td>
<td>0.67 ± 0.02 ± 0.01</td>
</tr>
<tr>
<td>ALEPH</td>
<td>PLB 492, 259 (2000)</td>
<td>0.84 ± 0.82 ± 0.16</td>
</tr>
<tr>
<td>OPAL</td>
<td>EPJ C5, 379 (1998)</td>
<td>3.20 ± 1.80 ± 0.50</td>
</tr>
<tr>
<td>CDF</td>
<td>PRD 61, 072005 (2000)</td>
<td>0.79 ± 0.41</td>
</tr>
<tr>
<td>LHCb</td>
<td>PLB 721 (2013)</td>
<td>0.73 ± 0.07 ± 0.04</td>
</tr>
<tr>
<td>Belle5S</td>
<td>PRL 108 (2012)</td>
<td>0.57 ± 0.58 ± 0.06</td>
</tr>
<tr>
<td>Average</td>
<td>HFAG</td>
<td>0.68 ± 0.02</td>
</tr>
</tbody>
</table>

Another taste of things to come (not yet world leading for this measurement)
Constraint from $\beta$ measurement

$\beta \equiv \phi_1$

$\beta = (21.5 \pm 0.8)^\circ$
Measurement of $\alpha$

- Time-dependent CP violation in modes dominated by $b \to u\bar{u}d$ tree diagrams probes $\alpha$ (or $\pi-(\beta+\gamma)$)
  - $C = 0 \& S = +\eta_{\text{CP}} \sin(2\alpha)$

- $b \to duu\bar{u}$ penguin transitions contribute to same final states $\Rightarrow$ “penguin pollution”
  - $C \neq 0 \Leftrightarrow$ direct CP violation can occur
  - $S \neq +\eta_{\text{CP}} \sin(2\alpha)$

- Two approaches (optimal approach combines both)
  - try to use modes with small penguin contribution
  - correct for penguin effect (isospin analysis)
$B^0 \rightarrow \pi^+\pi^-$ - Experimental Situation

Large penguin effect
Large direct CP violation

Contours give $-2\Delta \ln L = \Delta \chi^2 = 1$, corresponding to 68.3% CL for 2 dof
Isospin analysis

- Use triangle construction to find difference ($\theta$) between “$\alpha_{\text{eff}}$” and $\alpha$
- Requires measurement of rates and asymmetries of $B^+ \rightarrow \pi^+\pi^0$ & $B^0 \rightarrow \pi^0\pi^0$
$B^0 \rightarrow \rho^+ \rho^-$ -- Experimental Situation

Small penguin effect
Small direct CP violation

Contours give $-2\Delta \ln L = \Delta \chi^2 = 1$, corresponding to 60.7% CL for 2 dof
Measurement of $\alpha$

$\alpha = (85.4^{+4.0}_{-3.8})^\circ$

These solutions ruled out by observation of direct CP violation in $B_0 \to \pi^+ \pi^-$
Consistency of measurements with the KM mechanism

Different statistical approaches

... same answer
Where we are now ... and what's coming next

- Measurements of the CKM matrix elements and properties of the Unitarity Triangle are consistent with the Standard Model
  - Nobel Prize for Kobayashi and Maskawa in 2008
- Constraints for (beyond standard) model builders
  - Minimal Flavour Violation?
- Several hints (~3σ) for new physics
  - Plenty of room still for discoveries
  - Some sectors relatively unexplored
- Need next generation of flavour physics experiments
Constraints on NP from mixing

- All measurements of $\Delta m$ & $\Delta \Gamma$ consistent with SM
  - $K^0$, $D^0$, $B_d^0$ and $B_s^0$
- This means $|A_{NP}| < |A_{SM}|$ where $A_{SM}^{\Delta F=2} \approx \frac{G_F m_t^2}{16\pi^2} (V_{ti} V_{tj})^2 \times \langle M | (\bar{Q}_L \gamma^\mu Q_{Lj}) \rangle^2 |M| \times F \left( \frac{M_W^2}{m_t^2} \right)$
- Express NP as perturbation to the SM Lagrangian
  - couplings $c_i$ and scale $\Lambda > m_w$
- For example, SM like (left-handed) operators

\[
\Delta \mathcal{L}^{\Delta F=2} = \sum_{i \neq j} \frac{c_i}{\Lambda^2} (\bar{Q}_L \gamma^\mu Q_{Lj})^2
\]

<table>
<thead>
<tr>
<th>Operator</th>
<th>Bounds on $\Lambda$ in TeV ($c_{ij} = 1$)</th>
<th>Bounds on $c_{ij}$ ($\Lambda = 1$ TeV)</th>
<th>Observables</th>
</tr>
</thead>
<tbody>
<tr>
<td>$(\bar{s}_L \gamma^\mu d_L)^2$</td>
<td>$9.8 \times 10^2$</td>
<td>$1.6 \times 10^4$</td>
<td>$9.0 \times 10^{-7}$</td>
</tr>
<tr>
<td>$(\bar{s}_R d_L)(\bar{s}_L d_R)$</td>
<td>$1.8 \times 10^4$</td>
<td>$3.2 \times 10^5$</td>
<td>$6.9 \times 10^{-9}$</td>
</tr>
<tr>
<td>$(\bar{c}_L \gamma^\mu u_L)^2$</td>
<td>$1.2 \times 10^3$</td>
<td>$2.9 \times 10^3$</td>
<td>$5.6 \times 10^{-7}$</td>
</tr>
<tr>
<td>$(\bar{c}_R u_L)(\bar{c}_L u_R)$</td>
<td>$6.2 \times 10^3$</td>
<td>$1.5 \times 10^4$</td>
<td>$5.7 \times 10^{-8}$</td>
</tr>
<tr>
<td>$(\bar{b}_L \gamma^\mu d_L)^2$</td>
<td>$5.1 \times 10^2$</td>
<td>$9.3 \times 10^2$</td>
<td>$3.3 \times 10^{-6}$</td>
</tr>
<tr>
<td>$(\bar{b}_R d_L)(\bar{b}_L d_R)$</td>
<td>$1.9 \times 10^3$</td>
<td>$3.6 \times 10^3$</td>
<td>$5.6 \times 10^{-7}$</td>
</tr>
<tr>
<td>$(\bar{b}_L \gamma^\mu s_L)^2$</td>
<td>$1.1 \times 10^2$</td>
<td>$7.6 \times 10^{-5}$</td>
<td>$\Delta m_B$</td>
</tr>
<tr>
<td>$(\bar{b}_R s_L)(\bar{b}_L s_R)$</td>
<td>$3.7 \times 10^2$</td>
<td>$1.3 \times 10^{-5}$</td>
<td>$\Delta m_{B_s}$</td>
</tr>
</tbody>
</table>
New Physics Flavour Problem

- Limits on NP scale at least 100 TeV for generic couplings
  - model-independent argument, also for rare decays
- But we need NP at the TeV scale to solve the hierarchy problem (and to provide DM candidate, etc.)
- So we need NP flavour-changing couplings to be small
- Why?
  - minimal flavour violation?
    - perfect alignment of flavour violation in NP and SM
  - some other approximate symmetry?
  - flavour structure tells us about physics at very high scales
- There are still important observables that are not yet well-tested
Searches for New Physics

• Massive, beyond SM, particles may contribute to B decay processes in loop diagrams
  – same true for kaon, charm & charged lepton physics
  – strong constraints in NP model building (flavour problem)
• Particularly interesting (not yet well tested) are $b \to s$
  – $B_s$ mixing
  – $b \to sg$ (eg. time-dependence in $B^0 \to \phi K_S$, etc.)
  – $b \to sy$ (eg. rates and moments, TDCPV in $B^0 \to K_S \pi^0 \gamma$)
  – $b \to sl^+l^-$ (eg. FB asymmetry in $B \to K^*l^+l^-$)
  – $b \to sv\nu$ (also $s \to d\nu\nu$)
Like-sign dimuon asymmetry

- Semileptonic decays are flavour-specific
- B mesons are produced in BB pairs
- Like-sign leptons arise if one of BB pair mixes before decaying
- If no CP violation in mixing $N(++) = N(---)$
- Inclusive measurement $\leftrightarrow$ contributions from both $B_d^0$ and $B_s^0$
  - relative contributions from production rates, mixing probabilities & SL decay rates

D0 experiment
Phys.Rev. D89 (2014) 012002

$3.6\sigma$
# Flavour physics at hadron colliders

<table>
<thead>
<tr>
<th></th>
<th>$e^+ e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$</th>
<th>$p\bar{p} \rightarrow b\bar{b}X$ ($\sqrt{s} = 2\text{ TeV}$)</th>
<th>$pp \rightarrow b\bar{b}X$ ($\sqrt{s} = 14\text{ TeV}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PEP-II, KEKB</strong></td>
<td></td>
<td>Tevatron</td>
<td>LHC</td>
</tr>
<tr>
<td><strong>Production cross-section</strong></td>
<td>1 nb</td>
<td>$\sim 100 \mu b$</td>
<td>$\sim 500 \mu b$</td>
</tr>
<tr>
<td><strong>Typical $b\bar{b}$ rate</strong></td>
<td>10 Hz</td>
<td>$\sim 100 \text{kHz}$</td>
<td>$\sim 500 \text{kHz}$</td>
</tr>
<tr>
<td><strong>Pile-up</strong></td>
<td>0</td>
<td>1.7</td>
<td>0.5–20</td>
</tr>
<tr>
<td><strong>$b$ hadron mixture</strong></td>
<td>$B^+ B^- (50%), B^0 \bar{B}^0 (50%)$</td>
<td>$B^+ (40%), B^0 (40%), B_s^0 (10%), \Lambda_b^0 (10%), \text{ others (&lt; 1%)}$</td>
<td></td>
</tr>
<tr>
<td><strong>$b$ hadron boost</strong></td>
<td>small ($\beta \gamma \sim 0.5$)</td>
<td>large ($\beta \gamma \sim 100$)</td>
<td></td>
</tr>
<tr>
<td><strong>Underlying event</strong></td>
<td>$B\bar{B}$ pair alone</td>
<td>Many additional particles</td>
<td></td>
</tr>
<tr>
<td><strong>Production vertex</strong></td>
<td>Not reconstructed</td>
<td>Reconstructed from many tracks</td>
<td></td>
</tr>
<tr>
<td><strong>$B^0 - \bar{B}^0$ pair production</strong></td>
<td>Coherent (from $\Upsilon(4S)$ decay)</td>
<td>Incoherent</td>
<td></td>
</tr>
<tr>
<td><strong>Flavour tagging power</strong></td>
<td>$\varepsilon D^2 \sim 30%$</td>
<td>$\varepsilon D^2 \sim 5%$</td>
<td></td>
</tr>
</tbody>
</table>
Geometry

- In high energy collisions, $b\bar{b}$ pairs produced predominantly in forward or backward directions.
- LHCb is a forward spectrometer.
Material imaged used beam gas collisions
RICH

LHCb
\(\sqrt{s} = 7\) TeV Data

\(K \rightarrow K\)

\(\pi \rightarrow K\)

Momentum (MeV/c)

Efficiency

\(\Delta LL(K \times z) > 0\)
\(\Delta LL(K - z) > 5\)
LHCb integrated luminosity

Instantaneous luminosity (2012) \sim 4 \times 10^{32} / \text{cm}^2 / \text{s}

LHCb design luminosity: 2 \times 10^{32} / \text{cm}^2 / \text{s}
**PROTON PHYSICS: STABLE BEAMS**

Energy: 3500 GeV  \( I(B1): 1.63 \times 10^{14} \)  \( I(B2): 1.61 \times 10^{14} \)

**Comments 03-10-2011 01:37:51:**

***STABLE BEAMS***

!!! CONGRATULATIONS TO LHCb !!!

!!! FOR THEIR 1ST 1.00/fb !!!

**Note “luminosity levelling”**

---

**BIS status and SMP flags**

- Link Status of Beam Permits: true, true
- Global Beam Permit: true, true
- Setup Beam: false, false
- Beam Presence: true, true
- Moveable Devices Allowed In Stable Beams: true, true

**PM Status**

- B1: ENABLED
- B2: ENABLED
What does $\int L dt = 1/fb$ mean?

- Measured cross-section, in LHCb acceptance
  \[ \sigma(pp \rightarrow bbX) = (75.3 \pm 5.4 \pm 13.0) \mu b \]
  PLB 694 (2010) 209

- So, number of $bb$ pairs produced in 1/fb (2011 sample)
  \[ 10^{15} \times 75.3 \times 10^{-6} \sim 10^{11} \]

- Compare to combined data sample of $e^+e^-$ “B factories” BaBar and Belle of $\sim 10^9 BB$ pairs
  for any channel where the (trigger, reconstruction, stripping, offline) efficiency is not too small, LHCb has world's largest data sample

- p.s.: for charm, $\sigma(pp \rightarrow c\bar{c}X) = (6.10 \pm 0.93) \text{ mb}$
  LHCb-CONF-2010-013
The all important trigger

Challenge is
- to efficiently select most interesting B decays
- while maintaining manageable data rates

Main backgrounds
- “minimum bias” inelastic pp scattering
- other charm and beauty decays

Handles
- high $p_T$ signals (muons)
- displaced vertices
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 ($x_D = \Delta m_D / \Gamma_D$ & $y_D = 2\Delta \Gamma_D / \Gamma_D$) 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

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

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

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

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

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

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

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

CP violating asymmetries

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

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

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

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

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

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

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

\[
\Gamma(B_s(t) \to f) = \mathcal{N}_f |A_f|^2 \frac{1 + |\lambda_f|^2}{2} e^{-\Gamma t} \\
\times \left[ \cosh \frac{\Delta \Gamma t}{2} + 0 \right] + \mathcal{A}_{\Delta \Gamma} \sinh \frac{\Delta \Gamma t}{2} + \mathcal{A}_{\text{CP}}^{\text{mix}} \sin (\Delta m t) \\
\Gamma(B_s(t) \to f) = \mathcal{N}_f |A_f|^2 \frac{1 + |\lambda_f|^2}{2} (1 + \text{0}) e^{-\Gamma t} \\
\times \left[ \cosh \frac{\Delta \Gamma t}{2} - 0 \right] + \mathcal{A}_{\Delta \Gamma} \sinh \frac{\Delta \Gamma t}{2} - \mathcal{A}_{\text{CP}}^{\text{mix}} \sin (\Delta m t) .
\]

- 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

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

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

- 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

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

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

- 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
\[ \Phi_s = -2\beta_s \]

- Most attractive channel
  \[ B_s^0 \rightarrow J/\psi \phi \]

- 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 (\( \Gamma_s, \Delta \Gamma_s \))
\( B_s \to J/\psi \phi \) formalism

\( B_s \to J/\psi \phi \) (→ \( \mu^+ \mu^- K^+ K^- \)) is golden channel to study \( B_s \) oscillations ...

... but not a pure CP eigenstate

\[ \frac{d^4\Gamma(B_s^0 \to J/\psi\phi)}{dt \, d\cos \theta \, d\varphi \, d\cos \psi} = \frac{d^4\Gamma}{dt \, d\Omega} \times \sum_{k=1}^{6} h_k(t) \, f_k(\Omega) \]

<table>
<thead>
<tr>
<th>( k )</th>
<th>( h_k(t) )</th>
<th>( \bar{h}_k(t) )</th>
<th>( f_k(\theta, \psi, \varphi) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(</td>
<td>A_0(t)</td>
<td>^2 )</td>
</tr>
<tr>
<td>2</td>
<td>(</td>
<td>A_1(t)</td>
<td>^2 )</td>
</tr>
<tr>
<td>3</td>
<td>( A_1(t)^2 )</td>
<td>( A_1(t)^2 )</td>
<td>( \sin^2 \psi \sin^2 \theta )</td>
</tr>
<tr>
<td>4</td>
<td>( \Im {A_0(t)A_1(t)} )</td>
<td>( \Im {A_0(t)A_1(t)} )</td>
<td>( \sin \theta \sin 2\theta \sin \varphi )</td>
</tr>
<tr>
<td>5</td>
<td>( \Re {A_0(t)A_1(t)} )</td>
<td>( \Re {A_0(t)A_1(t)} )</td>
<td>( \frac{1}{\sqrt{2}} \sin 2\varphi \sin \varphi )</td>
</tr>
<tr>
<td>6</td>
<td>( \Im {A_0(t)A_1(t)} )</td>
<td>( \Im {A_0(t)A_1(t)} )</td>
<td>( \frac{1}{\sqrt{2}} \sin 2\theta \sin 2\varphi )</td>
</tr>
</tbody>
</table>

\(|A_0(0)|^2 = |A_0(0)|^2 e^{-\Gamma_{st}t} \left[ \cosh \left( \frac{\Delta m_s T}{2} \right) - \cos \Phi \sinh \left( \frac{\Delta m_s T}{2} \right) - \sin \Phi \sin (\Delta m_s T) \right] , \]

\(|A_{||}(0)|^2 = |A_{||}(0)|^2 e^{-\Gamma_{st}t} \left[ \cosh \left( \frac{\Delta m_s T}{2} \right) - \cos \Phi \sinh \left( \frac{\Delta m_s T}{2} \right) - \sin \Phi \sin (\Delta m_s T) \right] , \]

\(|A_{\perp}(0)|^2 = |A_{\perp}(0)|^2 e^{-\Gamma_{st}t} \left[ \cosh \left( \frac{\Delta m_s T}{2} \right) + \cos \Phi \sinh \left( \frac{\Delta m_s T}{2} \right) + \sin \Phi \sin (\Delta m_s T) \right] , \]

\( \Im \{A_{||}(t)A_{\perp}(t)\} = |A_{||}(0)||A_{\perp}(0)|e^{-\Gamma_{st}t} \left[ -\cos (\delta_{||} - \delta_{\perp}) \sin \Phi \sinh \left( \frac{\Delta m_s T}{2} \right) \right] , \]

\( \Re \{A_0(t)A_{||}(t)\} = |A_0(0)||A_{||}(0)|e^{-\Gamma_{st}t} \cos \delta_{||} \left[ \cosh \left( \frac{\Delta m_s T}{2} \right) - \cos \Phi \sinh \left( \frac{\Delta m_s T}{2} \right) \right] , \]

\( \Im \{A_0(t)A_{\perp}(t)\} = |A_0(0)||A_{\perp}(0)|e^{-\Gamma_{st}t} \left[ -\cos \delta_{\perp} \sin \Phi \sinh \left( \frac{\Delta m_s T}{2} \right) \right] , \]

\( \Im \{A_0(t)A_{\perp}(t)\} = |A_0(0)||A_{\perp}(0)|e^{-\Gamma_{st}t} \left[ -\cos \delta_{\perp} \sin \Phi \sinh \left( \frac{\Delta m_s T}{2} \right) \right] , \]

\( \Im \{A_{||}(t)A_{\perp}(t)\} = |A_{||}(0)||A_{\perp}(0)|e^{-\Gamma_{st}t} \left[ -\cos \delta_{\perp} \sin \Phi \sinh \left( \frac{\Delta m_s T}{2} \right) \right] , \]

\( \Im \{A_0(t)A_{\perp}(t)\} = |A_0(0)||A_{\perp}(0)|e^{-\Gamma_{st}t} \left[ -\cos \delta_{\perp} \sin \Phi \sinh \left( \frac{\Delta m_s T}{2} \right) \right] , \]
Current $B_s \rightarrow J/\psi\phi$ world average

- LHCb ≤1.0 fb$^{-1}$ + CDF 9.6 fb$^{-1}$ + DØ 8 fb$^{-1}$ + ATLAS 4.9 fb$^{-1}$

68% CL contours
($\Delta \log \mathcal{L} = 1.15$)

... significant improvement possible from data in hand at LHCb & ATLAS (&CMS)
\[ B \rightarrow K^* \mu^+ \mu^- \]

- \( b \rightarrow s l^+ l^- \) 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)

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

- \( Q_n \) – 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 \( b \to s\gamma \)), \( C_9 \) and \( C_{10} \)
Effective operators

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

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

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

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

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

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

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

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

This term gives a forward-backward asymmetry
Forward-backward asymmetry in $B \rightarrow K^* \mu^+ \mu^-$

Zero crossing-point

$q^2_0 = (4.9 \pm 0.9) \text{ GeV}^2/c^4$

(consistent with SM)

JHEP 08 (2013) 131
Another angular observable in $B \rightarrow K^* \mu^+ \mu^-$

Possible discrepancy with SM

PRL 111 (2013) 191801
$B_s \rightarrow \mu^+ \mu^-$

Killer app. for new physics discovery

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

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

- Was considered one of the hottest channels for early NP discovery at LHC ($B_d \rightarrow \mu^+ \mu^-$ also interesting ...)
$B_{(s)}^0 \rightarrow \mu^+\mu^-$

Searches over 30 years
\[ B^{0}_{(s)} \rightarrow \mu^+\mu^- \text{ – analysis ingredients} \]

- 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
$B_{(s)}^{0} \rightarrow \mu^{+}\mu^{-}$

latest results from CMS & LHCb

CMS PRL 111 (2013) 101804

LHCb PRL 111 (2013) 101805

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

LHCb

BDT > 0.7

3 fb\(^{-1}\)

4.0σ

Only events with BDT > 0.7
$B^{0}_{(s)} \rightarrow \mu^+ \mu^- - \text{combined results}$

$$B(B^0_s \rightarrow \mu^+ \mu^-) = (2.9 \pm 0.7) \times 10^{-9}$$
The Future of Flavour Physics

• charged lepton sector
  – proposals for improved measurements of many processes (often using new facilities built for other purposes)

• kaon system
  – search for $K \rightarrow \pi\nu\nu$ [the holy grail] continues

• charm system
  – BESIII @ BEPC has taken over from CLEO-c
  – charm also studied at LHCb and B factories

• B system
  – Belle2 will be online 2016 / LHCb upgrade 2019
To obtain x40 higher luminosity.
Belle II Detector

KL and muon detector:
- Resistive Plate Counter (barrel outer layers)
- Scintillator + WLSF + MPPC (end-caps, inner 2 barrel layers)

Particle Identification
- Time-of-Propagation counter (barrel)
- Prox. focusing Aerogel RICH (fwd)

EM Calorimeter:
- CsI(Tl), waveform sampling (barrel)
- Pure CsI + waveform sampling (end-caps)

Central Drift Chamber
- He(50%):C₂H₆(50%), small cells, long lever arm, fast electronics

Beryllium beam pipe
- 2cm diameter

Vertex Detector
- 2 layers DEPFET + 4 layers DSSD

Electrons (7GeV)

Positrons (4GeV)
LHC upgrade and the all important trigger

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

- 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

Technical decisions all made! TDRs getting approved
Summary

• CKM mechanism accurately describes quark mixing and CP violation within the Standard Model

• Flavour physics is, and will remain, an essential tool to search for and diagnose new physics

• Not covered
  – Grand Unification
  – Baryon asymmetry of the Universe
References and background reading

- Heavy Flavour Averaging Group (HFAG)
  - http://www.slac.stanford.edu/xorg/hfag/

- CKMfitter
  - http://ckmfitter.in2p3.fr/

- UTFit
  - http://www.utfit.org/

- Documentation available from above web sites
References and background reading

• Reviews in the Particle Data Group (PDG)'s Review of Particle Physics
  - Quark Model [C.Amsler, T.DeGrand & B.Krusche]
  - Rare Kaon Decays [L.Littenberg & G.Valencia]
  - CP Violation in Meson Decays [D.Kirkby & Y.Nir]
  - CKM quark mixing matrix [A.Ceccucci, Z.Ligeti & Y.Sakai]
  - Determination of $V_{cb}$ and $V_{ub}$ [R.Kowalewski & T.Mannel]
  - $V_{ud}$, $V_{us}$, the Cabibbo Angle and CKM Unitarity [E.Blucher & W.J.Marciano]
References and background reading

- Most introductory particle physics books contain some background on flavour physics
  - eg. Perkins, Martin & Shaw
- Feynman lectures has an interesting chapter on lifetimes in the neutral kaon system
- More detailed books on quark flavour physics
  - CP violation, I.I.Bigi and A.I.Sanda (CUP)
  - CP violation, G.C.Branco, L.Lavoura & J.P.Silva (OUP)