Flavour Physics in the LHC Era
Lecture 1 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 hope to cover Part 1 & start Part 2

(but let's see how we go)
What is the LHC era?

Probably already out-of-date

... it is the foreseeable future!
What is flavour physics?

Flavour (particle physics)

In particle physics, flavour or flavor is a quantum number of elementary particles. In quantum chromodynamics, flavour is a global symmetry. In the electroweak theory, on the other hand, this symmetry is broken, and flavour-changing processes exist, such as quark decay or neutrino oscillations.

“The term flavor was first used in particle physics in the context of the quark model of hadrons. It was coined in 1971 by Murray Gell-Mann and his student at the time, Harald Fritzsch, at a Baskin-Robbins ice-cream store in Pasadena. Just as ice cream has both color and flavor so do quarks.”

RMP 81 (2009) 1887

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Flavour Physics
What is flavour physics?

<table>
<thead>
<tr>
<th>Fermions (&quot;matter&quot;)</th>
<th>Bosons (&quot;forces&quot;)</th>
</tr>
</thead>
<tbody>
<tr>
<td>{ Quarks \underline{ uuu } \underline{ ccc } \underline{ ttt }  \   \underline{ ddd } \underline{ sss } \underline{ bbb }  \   \underline{ Leptons } \underline{ e } \underline{ \mu } \underline{ \tau }  \   \underline{ \nu_e } \underline{ \nu_{\mu} } \underline{ \nu_{\tau} }  }</td>
<td>{ \underline{ gggg gggg }  \   \underline{ \gamma }  \   \underline{ W^+ }  \   \underline{ W^- }  \   \underline{ Z }  \   \underline{ H }  }</td>
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Flavour Physics
Parameters of the Standard Model

- 3 gauge couplings
- 2 Higgs parameters
- 6 quark masses
- 3 quark mixing angles + 1 phase
- 3 (+3) lepton masses
- (3 lepton mixing angles + 1 phase)

( ) = with Dirac neutrino masses
Parameters of the Standard Model

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CKM matrix
PMNS matrix
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Mysteries of flavour physics

• Why are there so many different fermions?
• What is responsible for their organisation into generations / families?
• Why are there 3 generations / families each of quarks and leptons?
• Why are there flavour symmetries?
• What breaks the flavour symmetries?
• What causes matter–antimatter asymmetry?
Mysteries of flavour physics

- Why are there so many different fermions?
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Leave these to other lecturers ...
Reducing the scope

- Flavour physics includes
  - Neutrinos
  - Charged leptons
  - Kaon physics
  - Charm & beauty physics
  - (Some aspects of) top physics

- My focus will be on charm & beauty
  - will touch on others when appropriate
Heavy quark flavour physics

- Focus in these lectures will be on
  - flavour-changing interactions of charm and beauty quarks
- But quarks feel the strong interaction and hence hadronise
  - various different charmed and beauty hadrons
  - many, many possible decays to different final states
- The hardest part of quark flavour physics is learning the names of all the damned hadrons!
- On the other hand, hadronisation greatly increases the observability of CP violation effects
  - the strong interaction can be seen either as the “unsung hero” or the “villain” in the story of quark flavour physics
Why is heavy flavour physics interesting?

• Hope to learn something about the mysteries of the flavour structure of the Standard Model

• CP violation and its connection to the matter–antimatter asymmetry of the Universe

• Discovery potential far beyond the energy frontier via searches for rare or SM forbidden processes
What breaks the flavour symmetries?

- In the Standard Model, the vacuum expectation value of the Higgs field breaks the electroweak symmetry.
- Fermion masses arise from the Yukawa couplings of the quarks and charged leptons to the Higgs field (taking $m_\nu = 0$).
- The CKM matrix arises from the relative misalignment of the Yukawa matrices for the up- and down-type quarks.
- Consequently, the only flavour-changing interactions are the charged current weak interactions:
  - no flavour-changing neutral currents (GIM mechanism)
  - not generically true in most extensions of the SM
  - flavour-changing processes provide sensitive tests.
Lepton flavour violation

• Why do we not observe the decay $\mu \rightarrow e\gamma$?
  – exact (but accidental) lepton flavour conservation in the SM with $m_\nu = 0$
  – SM loop contributions suppressed by $(m_\nu / m_W)^4$
  – but new physics models tend to induce larger contributions
    • unsuppressed loop contributions
    • generic argument, also true in most common models

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The muon to electron gamma (MEG) experiment at PSI

\[ \mu^+ \rightarrow e^+ \gamma \]

- positive muons → no muonic atoms
- continuous (DC) muon beam → minimise accidental coincidences

First results published
Expect improved limits (or discoveries) over the next few years

NPB 834 (2010) 1
MEG results

$B(\mu^+ \rightarrow e^+ \gamma) < 2.4 \times 10^{-12}$ @ 90% CL

PRL 107 (2011) 171801
Prospects for Lepton Flavour Violation

- MEG still taking data
- New generations of $\mu$ – e conversion experiments
  - COMET at J-PARC, followed by PRISM/PRIME
  - mu2e at FNAL, followed by Project X
  - Potential improvements of $O(10^4) – O(10^6)$ in sensitivities!
- $\tau$ LFV a priority for next generation $e^+e^-$ flavour factories
  - SuperKEKB/Belle2 at KEK & SuperB in Italy
  - $O(100)$ improvements in luminosity $\rightarrow O(10) – O(100)$ improvements in sensitivity (depending on background)
  - LHC experiments have some potential to improve $\tau \rightarrow \mu\mu\mu$
What causes the difference between matter and antimatter?

- The CKM matrix arises from the relative misalignment of the Yukawa matrices for the up- and down-type quarks

\[ V_{CKM} = U_u U_d^+ \]

- It is a 3x3 complex unitary matrix
  - described by 9 (real) parameters
  - 5 can be absorbed as phase differences between the quark fields
  - 3 can be expressed as (Euler) mixing angles
  - the fourth makes the CKM matrix complex (i.e. gives it a phase)
    - weak interaction couplings differ for quarks and antiquarks
    - CP violation
The Cabibbo-Kobayashi-Maskawa Quark Mixing Matrix

\[ V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \]

- A 3x3 unitary matrix
- Described by 4 real parameters – allows CP violation
  - PDG (Chau-Keung) parametrisation: \( \theta_{12}, \theta_{23}, \theta_{13}, \delta \)
  - Wolfenstein parametrisation: \( \lambda, A, \rho, \eta \)
- Highly predictive
Range of CKM phenomena

- nuclear transitions
- pion decays
- kaons
- hyperon decays
- tau decays
- neutrino interactions
- charm
- bottom
- top

- hadronic matrix elements
- chiral perturbation theory
- lattice QCD
- flavour symmetries
- heavy quark effective theories
- operator product expansion
- perturbative QCD
- dispersion relations

Specialized experiments:
- PIBETA
- NA48, KTeV, KLOE, ISTRA
- CHORUS
- KEDR, FOCUS, CLEO, BES
- BABAR, BELLE, LHCb
- ALEPH, DELPHI, L3, OPAL
- CDF, D0, ATLAS, CMS
A brief history of CP violation and Nobel Prizes

- **1964** – Discovery of CP violation in $K^0$ system

- **1973** – Kobayashi and Maskawa propose 3 generations

- **1980** – Nobel Prize to Cronin and Fitch

- **2001** – Discovery of CP violation in $B_d$ system

- **2008** – Nobel Prize to Kobayashi and Maskawa
Sakharov conditions

• Proposed by A.Sakharov, 1967

• Necessary for evolution of matter dominated universe, from symmetric initial state
  
  (1) baryon number violation
  
  (2) C & CP violation
  
  (3) thermal inequilibrium

• No significant amounts of antimatter observed

• \( \Delta N_B/N_Y = (N(\text{baryon}) - N(\text{antibaryon}))/N_Y \sim 10^{-10} \)
Dirac's prescience

Concluding words of 1933 Nobel lecture

“If we accept the view of complete symmetry between positive and negative electric charge so far as concerns the fundamental laws of Nature, we must regard it rather as an accident that the Earth (and presumably the whole solar system), contains a preponderance of negative electrons and positive protons. It is quite possible that for some of the stars it is the other way about, these stars being built up mainly of positrons and negative protons. In fact, there may be half the stars of each kind. The two kinds of stars would both show exactly the same spectra, and there would be no way of distinguishing them by present astronomical methods.”
Digression\(^3\): Are there antimatter dominated regions of the Universe?

- Possible signals:
  - Photons produced by matter-antimatter annihilation at domain boundaries – not seen
    - Nearby anti-galaxies ruled out
  - Cosmic rays from anti-stars
    - Best prospect: Anti\(^4\)He nuclei
  - Searches ongoing ...

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Searches for astrophysical antimatter

**Alpha Magnetic Spectrometer** Experiment on board the **International Space Station**

**Payload for AntiMatter Exploration and Light-nuclei Astrophysics** Experiment on board the **Resurs-DK1 satellite**

launched 16th May 2011

launched 15th June 2006

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Dynamic generation of BAU

• Suppose equal amounts of matter (X) and antimatter (\(\bar{X}\))
• X decays to
  – A (baryon number \(N_A\)) with probability \(p\)
  – B (baryon number \(N_B\)) with probability \((1-p)\)
• \(\bar{X}\) decays to
  – \(\bar{A}\) (baryon number \(-N_A\)) with probability \(\bar{p}\)
  – \(\bar{B}\) (baryon number \(-N_B\)) with probability \((1-\bar{p})\)
• Generated baryon asymmetry:
  – \(\Delta N_{TOT} = N_A p + N_B (1-p) - N_A \bar{p} - N_B (1-\bar{p}) = (p - \bar{p}) (N_A - N_B)\)
  – \(\Delta N_{TOT} \neq 0\) requires \(p \neq \bar{p}\) & \(N_A \neq N_B\)
CP violation and the BAU

• We can estimate the magnitude of the baryon asymmetry of the Universe caused by KM CP violation

\[
\frac{n_B - n_{\bar{B}}}{n_Y} \approx \frac{n_B}{n_Y} \sim \frac{J \times P_u \times P_d}{M^{12}}
\]

\[J = \cos(\theta_{12})\cos(\theta_{23})\cos^2(\theta_{13})\sin(\theta_{12})\sin(\theta_{23})\sin(\theta_{13})\sin(\delta)\]

\[P_u = (m_t^2 - m_c^2)(m_t^2 - m_u^2)(m_c^2 - m_u^2)\]

\[P_d = (m_b^2 - m_s^2)(m_b^2 - m_d^2)(m_s^2 - m_d^2)\]

• The Jarlskog parameter J is a parametrization invariant measure of CP violation in the quark sector: J \sim O(10^{-5})

• The mass scale M can be taken to be the electroweak scale O(100 \text{ GeV})

• This gives an asymmetry O(10^{-17})
  - much much below the observed value of O(10^{-10})

N.B. Vanishes for degenerate masses

PRL 55 (1985) 1039
We need more CP violation!

• Widely accepted that SM CPV insufficient to explain observed baryon asymmetry of the Universe

• To create a larger asymmetry, require
  – new sources of CP violation
  – that occur at high energy scales

• Where might we find it?
  – lepton sector: CP violation in neutrino oscillations
  – quark sector: discrepancies with KM predictions
  – gauge sector, extra dimensions, other new physics: precision measurements of flavour observables are generically sensitive to additions to the Standard Model
The neutrino sector

- Enticing possibility that neutrinos may be Majorana particles
  - provides connection with high energy scale
  - CP violation in leptons could be transferred to baryon sector (via B-L conserving processes)
- Requires
  - Determination of PMNS matrix
    - All mixing angles and CP phase must be non-zero
  - Experimental proof that neutrinos are Majorana
- Hope for answers to these questions within LHC era
Daya Bay measurement of $\theta_{13} \neq 0$

$\sin^2 2\theta_{13} = 0.092 \pm 0.016 \text{ (stat)} \pm 0.005 \text{ (syst)}$

PRL 108 (2012) 171803

Results also from RENO, T2K, MINOS, ...
Flavour for new physics discoveries
A lesson from history

• New physics shows up at precision frontier before energy frontier
  – GIM mechanism before discovery of charm
  – CP violation / CKM before discovery of bottom & top
  – Neutral currents before discovery of Z

• Particularly sensitive – loop processes
  – Standard Model contributions suppressed / absent
  – flavour changing neutral currents (rare decays)
  – CP violation
  – lepton flavour / number violation / lepton universality
Neutral meson oscillations

- We have flavour eigenstates $M^0$ and $\bar{M}^0$
  - $M^0$ can be $K^0$ (sd), $D^0$ (cu), $B^0_d$ (bd) or $B^0_s$ (bs)
- These can mix into each other
  - via short-distance or long-distance processes
- Time-dependent Schrödinger eqn.

$$i \frac{\partial}{\partial t} \left( \begin{array}{c} M^0 \\ \bar{M}^0 \end{array} \right) = H \left( \begin{array}{c} M^0 \\ \bar{M}^0 \end{array} \right) = \left( M - \frac{i}{2} \Gamma \right) \left( \begin{array}{c} M^0 \\ \bar{M}^0 \end{array} \right)$$

- $H$ is Hamiltonian; $M$ and $\Gamma$ are 2x2 Hermitian matrices

- CPT theorem: $M_{11} = M_{22}$ and $\Gamma_{11} = \Gamma_{22}$

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particle and antiparticle have equal masses and lifetimes
Solving the Schrödinger equation

- Physical states: eigenstates of effective Hamiltonian

\[ M_{S,L} = p M^0 \pm q \bar{M}^0 \]

p & q complex coefficients that satisfy \(|p|^2 + |q|^2 = 1\)

- CP conserved if physical states = CP eigenstates (\(|q/p| = 1\))

- Eigenvalues

\[ \lambda_{S,L} = m_{S,L} - \frac{1}{2}i\Gamma_{S,L} = (M_{11} - \frac{1}{2}i\Gamma_{11}) \pm (q/p)(M_{12} - \frac{1}{2}i\Gamma_{12}) \]

\[ \Delta m = m_L - m_S \quad \Delta \Gamma = \Gamma_S - \Gamma_L \]

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

\[ \Delta m\Delta \Gamma = 4 \text{Re}(M_{12}\Gamma_{12}^*) \]

\[ (q/p)^2 = (M_{12}^* - \frac{1}{2}i\Gamma_{12}^*)/(M_{12} - \frac{1}{2}i\Gamma_{12}) \]
Simplistic picture of mixing parameters

- $\Delta m$: value depends on rate of mixing diagram
  - together with various other constants ...
    \[
    \Delta m_d = \frac{G_F^2}{6\pi^2} m_W^2 \eta_b S(x_t) m_{B_d} f_{B_d}^2 \hat{B}_{B_d} |V_{tb}|^2 |V_{td}|^2
    \]
  - that can be made to cancel in ratios

- $\Delta \Gamma$: value depends on widths of decays into common final states (CP-eigenstates)
  - large for $K^0$, small for $D^0$ & $B_d^0$

- $q/p \approx 1$ if $\arg(\Gamma_{12}/M_{12}) \approx 0$ ($|q/p| \approx 1$ if $M_{12} \ll \Gamma_{12}$ or $M_{12} \gg \Gamma_{12}$)
  - CP violation in mixing when $|q/p| \neq 1$

$\Delta m_d \over \Delta m_s = \frac{m_{B_d} f_{B_d}^2 \hat{B}_{B_d}}{m_{B_s} f_{B_s}^2 \hat{B}_{B_s}} \left| \frac{V_{td}}{V_{ts}} \right|^2$

\[
\epsilon = \frac{p-q}{p+q} \neq 0
\]
Simplistic picture of mixing parameters

<table>
<thead>
<tr>
<th></th>
<th>$\Delta m$</th>
<th>$\Delta \Gamma$</th>
<th>$q/p$</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>($x = \Delta m/\Gamma$)</td>
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<td>($\varepsilon = (p-q)/(p+q)$)</td>
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<td>$K^0$</td>
<td>large</td>
<td>$\sim$ maximal</td>
<td>small</td>
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<td></td>
<td>$\sim 500$</td>
<td>$\sim 1$</td>
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</tr>
</tbody>
</table>
### Simplistic picture of mixing parameters

<table>
<thead>
<tr>
<th>Particle</th>
<th>$\Delta m$ ($x = \Delta m/\Gamma$)</th>
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- **Well-measured only recently (see later)**
- **More precise measurements needed** *(SM prediction well known)*
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 $A_{SM}^{\Delta F=2} \approx \frac{G_F m_l^2}{16\pi^2} (V_{ti} V_{tj})^2 \times \langle M | (\bar{Q}_L i \gamma^\mu Q_L)_j | M \rangle \times F \left( \frac{M^2_{W}}{m_l^2} \right)$
- Express NP as perturbation to the SM Lagrangian
  - couplings $c_i$ and scale $\Lambda > m_W$
- For example, SM like (left-handed) operators $\Delta \mathcal{L}^{\Delta F=2} = \sum_{i \neq j} c_{ij} \frac{(\bar{Q}_L i \gamma^\mu Q_L)_j}{\Lambda^2}$

\[
\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_{i} \frac{c_i^{(d)}}{\Lambda^{(d-4)}} O_i^{(d)} (\text{SM fields})
\]

<table>
<thead>
<tr>
<th>Operator</th>
<th>Bounds on $\Delta$ in TeV ($c_{ij} = 1$)</th>
<th>Bounds on $c_{ij}$ ($\Lambda = 1$ TeV)</th>
<th>Observables</th>
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<tbody>
<tr>
<td>$(\bar{s}_L \gamma^\mu d_L)^2$</td>
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</table>
Similar story – but including more (more up-to-date) inputs, and in pictures

\[ \Delta m_d & \Delta m_s \]

\[ \alpha_{\exp} \]

\[ \sin(\phi^d + 2\beta_d) > 0 \]

\[ \cos(\phi^d + 2\beta_d) > 0 \]

New Physics in \( B_d - \bar{B}_d \) mixing

\[ \Delta \Gamma_s & \tau_s^{(S)} \]

\[ \phi^s - 2\beta_s \]

New Physics in \( B_s - \bar{B}_s \) mixing

arXiv:1203.0238
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
Like-sign dimuon asymmetry

- Semileptonic decays are flavour-specific
- B mesons are produced in $B\bar{B}$ pairs
- Like-sign leptons arise if one of $B\bar{B}$ 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

\[
A_{SL} = \frac{(1 - |q/p|^4)}{(1+|q/p|^4)}
\]
Updated picture including new results (LHCb & D0) from ICHEP 2012

D0: arXiv:1207.1769 & ICHEP talk
LHCb: LHCb-CONF-2012-022

Situation unclear – improved measurements needed

Image credit: Anna Phan
http://www.quantumdiaries.org/2012/08/02/measuring-matter-antimatter-asymmetries/