Flavour Physics & CP Violation
Lecture 4 of 4

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Contents

• Part 1
  – What is flavour physics & why is it interesting?

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

• Part 3
  – What do we hope to learn from current experiments?

• Part 4
  – The future of flavour physics
Strong CP?

• I've told you that the CKM matrix is the only source of CP violation in the Standard Model.

• Is this true? What is “the Standard Model”? 
Strong CP?

• I've told you that the CKM matrix is the only source of CP violation in the Standard Model.

• Is this true? What is “the Standard Model”?

The SM

Input: Symmetries and fields

• Symmetry: 4d Poincare and

$$SU(3)_C \times SU(2)_L \times U(1)_Y$$

• Fields:
  • 3 copies of QUDLE fermions

$$Q_L(3, 2)_{1/6} \quad U_R(3, 1)_{2/3} \quad D_R(3, 1)_{-1/3}$$

$$L_L(1, 2)_{-1/2} \quad E_R(1, 1)_{-1}$$

• One scalar

$$\phi(1, 2)_{+1/2}$$

Then Nature is described by

Output: the most general $$\mathcal{L}$$

$$\mathcal{L} = \mathcal{L}_{\text{kin}} + \mathcal{L}_{\text{Higgs}} + \mathcal{L}_{\text{Yukawa}}$$

• The model can have SSB

$$\langle \phi \rangle = \left( \begin{array}{c} 0 \\ v/\sqrt{2} \end{array} \right) \Rightarrow SU(2)_L \times U(1)_Y \rightarrow U(1)_{\text{EM}}$$

• This model has a $$U(1)_B \times U(1)_e \times U(1)_\mu \times U(1)_\tau$$ accidental symmetry

• It has 18 parameters, and we measure them all by now

• We then made many tests and the SM basically passes almost all of them

Then QCD

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \frac{n_f g^2}{32\pi^2} F_{\mu\nu} \tilde{F}^{\mu\nu} + \bar{\psi} (i\gamma^\mu D_\mu - me^{i\theta/\gamma_5}) \psi$$
**Neutron electric dipole moment**

- If the $\theta_{QCD}$ parameter is $\neq 0$, there is CP violation in the strong interaction
  - $\rightarrow$ observable neutron electric dipole moment
- But: $|d_n| < 2.9 \times 10^{-26} \text{ e cm}$ \[^{(PRL 97 (2006) 131801)}\]

If neutron were the size of the earth, $+/-$ charges separated by $< 10 \mu m$
The strong CP problem

- But: \( |d_n| < 2.9 \times 10^{-26} \text{ e cm} \) (PRL 97 (2006) 131801)
- Correlates to \( \theta_{\text{QCD}} < 10^{-9} \)
  - Why is it so small? Is it zero?
  - Does some new symmetry forbid it?
  - e.g. Peccei-Quinn theory
    - predicts the axion
  - various experiments (e.g. CAST, PVLAS, ADMX) search for axions, which are also a potential dark matter candidate
Precision physics with electric & magnetic moments

• Electric dipole moments are CP violating
  – essentially zero in the SM, but can be much larger BSM with sources of flavour-conserving CPV
  \[ |d_e| < 8.7 \times 10^{-29} \text{ e cm} \]  
  [Science 343 (2014) 6168, 269]

• Magnetic dipole moments are CP conserving
  – sensitive to the structure of quantum fields
  • Dirac predicted \( g_e = 2 \) (RQM)
  • Schwinger predicted \( a_e = (g_e - 2)/2 = 0.0011614 \) (QED)
  • \( a_e \) now calculated to 10 loops in QED (PRL 109 (2012) 111807)
    – \( a_e = 0.00115965218178 \) (77)
(g-2)_\mu

New experiment at FNAL will reduce uncertainty by factor \sim 2

Improvements in theory uncertainties also anticipated
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 \((\tan \beta = \text{ratio of Higgs vevs})\)

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

- Clean experimental signature

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

 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 $B_s^0$ 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

![Graphs showing results from CMS and LHCb]

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

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

$B(B_s^0 \rightarrow \mu^+\mu^-) = (2.9\pm0.7) \times 10^{-9}$
\( B \rightarrow K^*\mu^+\mu^- \)

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

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

\( Q_n \) - 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 \( C_{10} \)
Theory of $B \rightarrow K^*\mu^+\mu^-$

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

This term gives a forward-backward asymmetry

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Angular analysis of $B^0 \rightarrow K^{*0} \mu^+\mu^-$

Analysis performed in bins of dimuon invariant mass squared ($q^2$)

LHCb JHEP 08 (2013) 131
See also CDF PRL 108 (2012) 081807,
BaBar PRD 86 (2012) 032012,
Belle PRL 103 (2009) 171801,
ATLAS-CONF-2013-038 &
CMS PLB 727 (2013) 77

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Angular analysis of $B^0 \rightarrow K^{*0}\mu^+\mu^-$

First measurement of zero-crossing point of $A_{FB}^q$

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

Consistent with SM expectation
New observables in $B^0 \rightarrow K^{*0} \mu^+ \mu^-$

Interesting tension with the SM prediction

LHCb PRL 111 (2013) 191801
Future flavour physics projects
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

**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**
- Introduce tracking/PID information, find displaced tracks/vertices
- 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

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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
LHCb upgrade timeline

- 2011
  - Letter of Intent: CERN-LHCC-2011-001

- 2012
  - Framework TDR: CERN-LHCC-2012-007
    - Endorsed by LHCC and approved by CERN Research Board (minutes)
    - LHCb upgrade features prominently in draft European Strategy for Particle Physics
  - See also arXiv:1208.3355 for physics discussion

- 2013
  - Sub-detector TDRs ← now approved

- 2014-17
  - Final R&D, production and construction

- 2018 (LS2)
  - Installation of upgraded LHCb detector (requires 18 months)
### Upgrade – expected sensitivities

<table>
<thead>
<tr>
<th>Type</th>
<th>Observable</th>
<th>Current precision</th>
<th>LHCb 2018</th>
<th>Upgrade (50 fb⁻¹)</th>
<th>Theory uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0_s$ mixing</td>
<td>$2\beta_s (B^0_s \to J/\psi \phi)$</td>
<td>0.10 [9]</td>
<td>0.025</td>
<td>0.008</td>
<td>$\sim 0.003$</td>
</tr>
<tr>
<td></td>
<td>$2\beta_s (B^0_s \to J/\psi f_0(980))$</td>
<td>0.17 [10]</td>
<td>0.045</td>
<td>0.014</td>
<td>$\sim 0.01$</td>
</tr>
<tr>
<td></td>
<td>$A_{FB}(B^0_s)$</td>
<td>$6.4 \times 10^{-3}$ [18]</td>
<td>$0.6 \times 10^{-3}$</td>
<td>$0.2 \times 10^{-3}$</td>
<td>$0.03 \times 10^{-3}$</td>
</tr>
<tr>
<td>Gluonic penguin</td>
<td>$2\beta_s^{\text{eff}} (B^0_s \to \phi \phi)$</td>
<td>–</td>
<td>0.17</td>
<td>0.03</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>$2\beta_s^{\text{eff}} (B^0_s \to K^{*0} K^{*0})$</td>
<td>–</td>
<td>0.13</td>
<td>0.02</td>
<td>$&lt; 0.02$</td>
</tr>
<tr>
<td></td>
<td>$2\beta_s^{\text{eff}} (B^0_s \to \phi K^0_S)$</td>
<td>0.17 [18]</td>
<td>0.30</td>
<td>0.05</td>
<td>0.02</td>
</tr>
<tr>
<td>Right-handed currents</td>
<td>$2\beta_s^{\text{eff}} (B^0_s \to \phi \gamma)$</td>
<td>–</td>
<td>0.09</td>
<td>0.02</td>
<td>$&lt; 0.01$</td>
</tr>
<tr>
<td></td>
<td>$\tau^{\text{eff}} (B^0_s \to \phi \gamma)/\tau_{B^0}$</td>
<td>–</td>
<td>5 %</td>
<td>1 %</td>
<td>0.2 %</td>
</tr>
<tr>
<td>Electroweak penguin</td>
<td>$S_3(B^0 \to K^{*0} \mu^+ \mu^-; 1 &lt; q^2 &lt; 6 \text{GeV}^2/c^4)$</td>
<td>0.08 [14]</td>
<td>0.025</td>
<td>0.008</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>$s_0 A_{FB}(B^0 \to K^{*0} \mu^+ \mu^-)$</td>
<td>25 % [14]</td>
<td>6 %</td>
<td>2 %</td>
<td>7 %</td>
</tr>
<tr>
<td></td>
<td>$A_1(K \mu^+ \mu^-; 1 &lt; q^2 &lt; 6 \text{GeV}^2/c^4)$</td>
<td>0.25 [15]</td>
<td>0.08</td>
<td>0.025</td>
<td>$\sim 0.02$</td>
</tr>
<tr>
<td></td>
<td>$B(B^+ \to \pi^+ \mu^+ \mu^-)/B(B^+ \to K^+ \mu^+ \mu^-)$</td>
<td>25 % [16]</td>
<td>8 %</td>
<td>2.5 %</td>
<td>$\sim 10 %$</td>
</tr>
<tr>
<td>Higgs penguin</td>
<td>$B(B^0_s \to \mu^+ \mu^-)$</td>
<td>$1.5 \times 10^{-9}$ [2]</td>
<td>$0.5 \times 10^{-9}$</td>
<td>$0.15 \times 10^{-9}$</td>
<td>$0.3 \times 10^{-9}$</td>
</tr>
<tr>
<td></td>
<td>$B(B^0 \to \mu^+ \mu^-)/B(B^0 \to \mu^+ \mu^-)$</td>
<td>–</td>
<td>$\sim 100 %$</td>
<td>$\sim 35 %$</td>
<td>$\sim 5 %$</td>
</tr>
<tr>
<td>Unitarity triangle</td>
<td>$\gamma (B \to D^{(<em>)} K^{(</em>)})$</td>
<td>$\sim 10-12 \degree$ [19, 20]</td>
<td>4 \degree</td>
<td>0.9 \degree</td>
<td>negligible</td>
</tr>
<tr>
<td></td>
<td>$\gamma (B^0_s \to D_s K)$</td>
<td>–</td>
<td>11 \degree</td>
<td>2.0 \degree</td>
<td>negligible</td>
</tr>
<tr>
<td>angles</td>
<td>$\beta (B^0 \to J/\psi K^0_S)$</td>
<td>0.8 \degree [18]</td>
<td>0.6 \degree</td>
<td>0.2 \degree</td>
<td>negligible</td>
</tr>
<tr>
<td>Charm CP violation</td>
<td>$A_T$</td>
<td>$2.3 \times 10^{-3}$ [18]</td>
<td>$0.40 \times 10^{-3}$</td>
<td>$0.07 \times 10^{-3}$</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>$\Delta A_{CP}$</td>
<td>$2.1 \times 10^{-3}$ [5]</td>
<td>$0.65 \times 10^{-3}$</td>
<td>$0.12 \times 10^{-3}$</td>
<td>–</td>
</tr>
</tbody>
</table>

Table 1: Statistical sensitivities of the LHCb upgrade to key observables. For each observable the current sensitivity is compared to that which will be achieved by LHCb before the upgrade, and that which will be achieved with 50 fb⁻¹ by the upgraded experiment. Systematic uncertainties are expected to be non-negligible for the most precisely measured quantities.

- sample sizes in most exclusive B and D final states far larger than those collected elsewhere
- no serious competition in study of $B_s$ decays and CP violation

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Other future flavour experiments

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

- Rare kaon decays
  - $K^+ \rightarrow \pi^+ \nu \nu$ (NA62, CERN); $K^0 \rightarrow \pi^0 \nu \nu$ (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 boson (2HDM or SUSY)

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

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

Belle PRD 82 (2010) 071101

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To obtain x40 higher luminosity

KEKB to SuperKEKB

Replace short dipoles with longer ones (LER)

Redesign the lattices of HER & LER to squeeze the emittance

TiN-coated beam pipe with antechambers

KEKB to SuperKEKB

Add / modify RF systems for higher beam current

New superconducting /permanent final focusing quads near the IP

Low emittance gun

Low emittance electrons to inject

New positron target / capture section

Damping ring

Low emittance positrons to inject

Positron source

New beam pipe & bellows

Colliding bunches

New IR

Belle II

KEKB to SuperKEKB

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)

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

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

Electrons (7GeV)

Beryllium beam pipe
2cm diameter

Vertex Detector
2 layers DEPFET + 4 layers DSSD

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

Positrons (4GeV)
Goal of Belle II/SuperKEKB

We will reach 50 ab\(^{-1}\) in 2022

Commissioning starts in 2015.

Shutdown for upgrade

9 months/year
20 days/month

Peter Križan, Ljubljana
The holy grail of kaon physics: $K \to \pi \nu \nu$

Next generation experiments should measure these decays for the 1$^{st}$ time

- $K^+ \to \pi^+ \nu \nu$ (NA62, CERN)
- $K^0 \to \pi^0 \nu \nu$ (K0T0, J-PARC)
- Proposals also at FNAL
NA62 Technique: Decay in Flight

\[ m_{\text{miss}}^2 = \left( \vec{p}_K - \vec{p}_\pi \right)^2 \]

Kinematically Constraint Decays

Unconstraint Decays

\(~92\% \text{ of Kaon decays}\)

\[ K^+ \rightarrow \pi^+ \pi^0 \]
[Region I]
[Region II]

\[ K^+ \rightarrow \pi^+ \pi^+ \pi^- \]

\[ K^+ \rightarrow e^+ \pi^0 \nu \]

\[ K^0 \rightarrow \mu^+ \pi^0 \nu \]

\[ K^0 \rightarrow \mu^+ \pi^+ \pi^- \nu \]

\[ K^0 \rightarrow e^+ \pi^0 \pi^- \nu \]
NA62: $K^+ \rightarrow \pi^+ \nu \nu$ in-flight @ CERN–SPS

SPS primary $p$: 400 GeV/c
Unseparated beam:
- 75 GeV/c
- 750 MHz
- $\pi/K/p \sim 6\% \; K^+$

Beam Line + Infra.

Decay Region 65m

Total Length 270m

CERN

UK

CEDAR

Gigatracker (GTK)

Measure Kaon:
- Time
- Angles
- Momentum

CERN

INFN

Belgium

TARGET

INFN

Italy

CHANTI

INFN

Small Angle Veto

SAV

Bulgaria

IHEP

INR

CHOD Charged Hodoscope

LKr

MUV

RICH

Mainz

IHEP

INR

US

JINR

CERN

INFN

Mexico
KOTO at JPARC
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

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

• 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)
Back up
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

... but SM also predicts that the photon is polarised
b → sγ photon polarisation measurement

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

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

Excellent prospects for LHCb with $B_s \rightarrow \phi \gamma$

NPB 867 (2013) 1

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First measurement of photon polarisation in $b \to s \gamma$ transitions

- New LHCb measurement
  - uses $B^+ \to K^+\pi\pi\gamma$ decays
  - compare $\gamma$ direction relative to $K^+\pi\pi$ plane

\[ A_{ud} = -0.085 \pm 0.019 \text{ (stat)} \pm 0.003 \text{ (syst)} \]

$A_{ud}$ proportional to polarisation

(unfortunately, constant of proportionality has large uncertainty)
Effective operators

\[ \mathcal{H}_{W}^{\Delta B=1, \Delta S=0, \Delta S=-1} = 4 \frac{G_F}{\sqrt{2}} \left( \frac{C_{1}(\mu)Q_{1}^{c}(\mu) + C_{2}(\mu)Q_{2}^{c}(\mu)}{\lambda_{\gamma}^{s}(C_{1}(\mu)Q_{1}^{u}(\mu) + C_{2}(\mu)Q_{2}^{u}(\mu)) - \lambda_{i}^{s} \sum_{i=3}^{10} C_{i}(\mu)Q_{i}(\mu)} \right) \]

where the \( \lambda_{q}^{s} = V_{q}^{*} V_{q} \) and the operator basis is given by

\[
\begin{align*}
Q_{1}^{q} &= \bar{b}_{L}^{\alpha} \gamma_{\mu} q_{L}^{\alpha} \bar{q}_{L}^{\beta} \gamma_{\mu} s_{L}^{\beta} \\
Q_{2}^{q} &= \bar{b}_{L}^{\alpha} \gamma_{\mu} q_{L}^{\alpha} \bar{q}_{L}^{\beta} \gamma_{\mu} s_{L}^{\beta} \\
Q_{3} &= \bar{b}_{L}^{\alpha} \gamma_{\mu} s_{L}^{\alpha} \sum_{q} \bar{q}_{L}^{\beta} \gamma_{\mu} q_{L}^{\beta} \\
Q_{4} &= \bar{b}_{L}^{\alpha} \gamma_{\mu} s_{L}^{\alpha} \sum_{q} \bar{q}_{L}^{\beta} \gamma_{\mu} q_{L}^{\beta} \\
Q_{5} &= \bar{b}_{L}^{\alpha} \gamma_{\mu} s_{L}^{\alpha} \sum_{q} \bar{q}_{R}^{\beta} \gamma_{\mu} q_{R}^{\beta} \\
Q_{6} &= \bar{b}_{L}^{\alpha} \gamma_{\mu} s_{L}^{\alpha} \sum_{q} \bar{q}_{R}^{\beta} \gamma_{\mu} q_{R}^{\beta} \\
Q_{7} &= \frac{3}{2} \bar{b}_{L}^{\alpha} \gamma_{\mu} s_{L}^{\alpha} \sum_{q} e_{q} \bar{q}_{R}^{\beta} \gamma_{\mu} q_{R}^{\beta} \\
Q_{8} &= \frac{3}{2} \bar{b}_{L}^{\alpha} \gamma_{\mu} s_{L}^{\alpha} \sum_{q} e_{q} \bar{q}_{R}^{\beta} \gamma_{\mu} q_{R}^{\beta} \\
Q_{9} &= \frac{3}{2} \bar{b}_{L}^{\alpha} \gamma_{\mu} s_{L}^{\alpha} \sum_{q} e_{q} \bar{q}_{L}^{\beta} \gamma_{\mu} q_{L}^{\beta} \\
Q_{10} &= \frac{3}{2} \bar{b}_{L}^{\alpha} \gamma_{\mu} s_{L}^{\alpha} \sum_{q} e_{q} \bar{q}_{L}^{\beta} \gamma_{\mu} q_{L}^{\beta} \\
\end{align*}
\]

Four-fermion operators (except \( Q_{7}\gamma \) & \( Q_{8g} \)) – dimension 6
Future projects

- Nuclear transitions
- Kaons
- Pion decays
- Hyperon decays
- Tau decays
- Neutrino interactions
- Charm
- Bottom
- Top
- Neutrino interactions

- KLOE-2, NA62, KOTO
- NA48, KTeV, KLOE-2, ISTRA
- Project X
- BABAR, BELLE, LHCb
- CHORUS
- Operator product expansion
- W decays
- Belle-2, SuperB, LHCb upgrade
- CDF, D0, ATLAS, CMS
- Great progress in theory anticipated
- Dispersion relations
- Hadronic matrix elements
- Chiral perturbation theory
- Lattice QCD
- Perturbative QCD
- Heavy quark effective theories
- Flavour symmetries
- Particles