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
CP violation searches in $D^0$ and $B^0_s$ systems
CP violation in neutral meson oscillations

- $K^0$:
  - CP violation in mixing discovered 1964
  - Nobel prize for Cronin & Fitch 1980

- $B^0$:
  - CP violation in mixing-decay interference discovered 2001
  - Nobel prize for Kobayashi & Maskawa 2008

- $D^0$ & $B_s^0$:
  - CP violation both in mixing and in mixing-decay interference expected to be tiny in SM
  - Good place to look for physics beyond the SM
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)

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Charm provides unique neutral meson “laboratory” to study CP violation effects in up-type quarks
\[ \Phi_s = -2\beta_s \]

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

- VV final state  
  three helicity amplitudes  
  \( \rightarrow \) mixture of CP-even and CP-odd  
  disentangled using angular & time-dependent distributions  
  \( \rightarrow \) additional sensitivity  
  many correlated variables  
  \( \rightarrow \) complicated analysis

- LHCb also uses  
  \[ B_s \to J/\psi f_0 (f_0 \to \pi^+\pi^-) \]
  - CP eigenstate; simpler analysis  
  - fewer events; requires input from \( J/\psi\phi \) analysis (\( \Gamma_s, \Delta\Gamma_s \))

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CP violation in $B_s^0 \to J/\psi\pi^+\pi^-$

$\phi_s = 70 \pm 68 \pm 8$ mrad

Asymmetry expected to be very small in the SM
CP violation in $B_s^0 \to J/\psi\phi$ & $J/\psi\pi\pi$

Analyses of $B_s^0 \to J/\psi\phi$ measure $\phi_s$ and $\Delta \Gamma_s$ simultaneously

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

Latest ATLAS results not yet included

Significant further improvement warranted for precise test of the SM prediction
CP violation in decay

(or “direct CP violation”)
Categories of CP violation

- Consider decay of neutral particle to a CP eigenstate

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

- \( |\frac{q}{p}| \neq 1 \) — CP violation in mixing

- \( |\frac{\bar{A}}{A}| \neq 1 \) — CP violation in decay

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

n.b. historical classification of CP violation as “direct” and “indirect” is of little use nowadays (though often misused!)
CP violation in decay

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

\[
A = |T| e^{i(\delta_T - \Phi_T)} + |P| e^{i(\delta_P - \Phi_P)} \quad \bar{A} = |T| e^{i(\delta_T + \Phi_T)} + |P| e^{i(\delta_P + \Phi_P)}
\]

\[
A_{CP} = \frac{|\bar{A}|^2 - |A|^2}{|\bar{A}|^2 + |A|^2} = \frac{2 |T| |P| \sin(\delta_T - \delta_P) \sin(\Phi_T - \Phi_P)}{|T|^2 + |P|^2 + 2 |T| |P| \cos(\delta_T - \delta_P) \cos(\Phi_T - \Phi_P)}
\]

Example: $B \to K\pi$
(weak phase difference is $\gamma$)

Feynman tree (a) and penguin (b) diagrams for the $B^0 \to K^+\pi^-$ decay
The famous penguin story

**Penguin diagram**

From Wikipedia, the free encyclopedia

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

**Origin of the name**

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

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

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

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

Example of a penguin diagram
The famous penguin story

Penguin diagram
From Wikipedia, the free encyclopedia

In quantum field theory, penguin diagrams are a class of Feynman diagrams which are important for understanding CP violating processes in the standard model. They were first isolated and studied by Mary K. Gaillard, Dimitri Nudakov, and Michael Stratton while we were working on neutrino oscillations. The penguin name came in 1977 from a comment made by John Ellis while we were working on the quark mass before it was found. I can remember the story well, I and Sergei Rudaz and I immediately started to try to associate the name with something meaningful to the work. A student at CERN, Melissa Freitas, was a New York penguin. She, I, and Sergei went to a party together. I lost my name because I was late, and was replaced by the word penguin at the end, and was replaced by New York 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 violation in $B \to K\pi$

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

\[ A_{CP}(K^-\pi^+) = -0.082 \pm 0.006 \]
\[ A_{CP}(K^-\pi^0) = +0.040 \pm 0.021 \]

“Kπ puzzle”

Could be a sign of new physics …
… but first need to rule out possibility of larger than expected QCD corrections

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Importance of $\gamma$ from $B \rightarrowDK$

- $\gamma$ 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 $\bar{D}^0$
y from combination of $B^+ \to DK^+$ modes

- All direct CP violation effects caused by $y$ in the Standard Model
- Only those in $B \to DK$ type processes involve only tree-level diagrams
  - enable determination of $y$ with negligible theoretical uncertainty
- Several different $B$ and $D$ decays can be used
- Combination includes results from GLW/ADS ($D \to hh$) & GGSZ ($D \to K_S hh$)
- Sensitivity: BaBar & Belle each $\sim 16^\circ$; latest LHCb $\sim 10^\circ$

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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
    \[ Q_L(3, 2)_{1/6}, U_R(3, 1)_{2/3}, D_R(3, 1)_{1/3} \]
    \[ L_L(1, 2)_{-1/2}, E_R(1, 1)_{-1} \]
  - 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
\[ \langle \phi \rangle = \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix} \Rightarrow SU(2)_L \times U(1)_Y \rightarrow U(1)_{\text{EM}} \]
- This model has a \( U(1)_B \times U(1)_C \times U(1)_\mu \times U(1)_\tau \) 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

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Neutron electric dipole moment

- If the $\theta_{QCD}$ parameter is $\neq 0$, there is CP violation in the strong interaction
  \[ \rightarrow \text{observable neutron electric dipole moment} \]
- 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 $< 10 \mu\text{m}$

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The strong CP problem

- But: $|d_n| < 2.9 \times 10^{-26}$ e cm (PRL 97 (2006) 131801)

- Corresponds to $\theta_{QCD} < 10^{-9}$
  - 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)
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 \((\tan \beta = \text{ratio of Higgs vevs})\)
  \[ BR(B_s \rightarrow \mu^+\mu^-)^{SM} = (3.3 \pm 0.3) \times 10^{-9} \quad BR(B_s \rightarrow \mu^+\mu^-)^{MSSM} \propto \tan^6 \beta / M_{A_0}^4 \]

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

Searches over 30 years

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

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

**Only events with BDT $>$ 0.7**
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 2σ 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 → K*⁰μ⁺μ⁻
  - superb laboratory for NP tests
  - experimentally clean signature
  - many kinematic variables …
  - … with clean theoretical predictions (at least at low q^2)
Angular analysis of $B \rightarrow K^* \mu^+ \mu^-$

- Differential decay distribution

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

$S_i$ terms related to Wilson coefficients and form factors

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

LHCb-CONF-2015-002

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Full angular analysis of $B^0 \to K^{*0} \mu^+ \mu^-$
Tension in $P'_5$

- Dimuon pair is predominantly spin-1 $P'_5$
- either vector (V) or axial-vector (A)
- There are 6 non-negligible amplitudes
  - 3 for VV and 3 for VA
  - expressed as $A^{L,R}_{0,\perp,\parallel}$ (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

$$P'_5 = \sqrt{2} \frac{\text{Re} \left( A^L_0 A^*_L - A^R_0 A^*_R \right)}{\sqrt{\left( |A^L_0|^2 + |A^R_0|^2 \right) \left( |A^L_L|^2 + |A^L_R|^2 + |A^R_L|^2 + |A^R_R|^2 \right)}}$$

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

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

$R_K (1 < q^2 < 6 \text{ GeV}^2) = 0.745^{+0.090}_{-0.074} \pm 0.036$

$<3\sigma$ from SM but suggestive
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 $5\sigma$ 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
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$^{st}$ 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

- 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 \( 2 \times 10^{33}/\text{cm}^2/\text{s} \)

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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
### 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>~ 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>~ 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>$2\beta^\text{eff}_s (B^0_s \to \phi \phi)$</td>
<td>–</td>
<td>0.17</td>
<td>0.03</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>$2\beta^\text{eff}_s (B^0_s \to K^{*0}K^{*0})$</td>
<td>–</td>
<td>0.13</td>
<td>0.02</td>
<td>&lt; 0.02</td>
</tr>
<tr>
<td></td>
<td>$2\beta^\text{eff}_s (B^0_s \to \phi K_S^0)$</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>$2\beta^\text{eff}_s (B^0_s \to \phi \gamma)$</td>
<td>–</td>
<td>0.09</td>
<td>0.02</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td></td>
<td>$\tau^\text{eff}_s (B^0_s \to \phi \gamma)$</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>~ 0.02</td>
</tr>
<tr>
<td></td>
<td>$\mathcal{B}(B^+ \to \pi^+ \mu^+ \mu^-)/\mathcal{B}(B^+ \to K^+ \mu^+ \mu^-)$</td>
<td>25% [16]</td>
<td>8%</td>
<td>2.5%</td>
<td>~ 10%</td>
</tr>
<tr>
<td>Higgs penguin</td>
<td>$\mathcal{B}(B^0_s \to \mu^+ \mu^-)$</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>$\mathcal{B}(B^0 \to \mu^+ \mu^-)/\mathcal{B}(B^0 \to \mu^+ \mu^-)$</td>
<td>–</td>
<td>~ 100%</td>
<td>~ 35%</td>
<td>~ 5%</td>
</tr>
<tr>
<td>Unitarity triangle</td>
<td>$\gamma (B \to D^{(<em>)}K^{(</em>)})$</td>
<td>~ 10–12° [19, 20]</td>
<td>4°</td>
<td>0.9°</td>
<td>negligible</td>
</tr>
<tr>
<td></td>
<td>$\gamma (B^0_s \to D_s K)$</td>
<td>–</td>
<td>11°</td>
<td>2.0°</td>
<td>negligible</td>
</tr>
<tr>
<td></td>
<td>$\beta (B^0 \to J/\psi K_S^0)$</td>
<td>0.8° [18]</td>
<td>0.6°</td>
<td>0.2°</td>
<td>negligible</td>
</tr>
<tr>
<td>Charm</td>
<td>$A_{\Gamma}$</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>CP violation</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
Other future flavour experiments

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

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

- **Muon to electron conversion (charged lepton flavour violation)**
  - COMET/PRIME (J-PARC); $\mu2e$ (FNAL)
  - also MEG upgrade & $\mu3e$ (PSI)

- **Various electric & magnetic dipole experiments**
  - $(g-2)\mu$ in FNAL & J-PARC
The holy grail of kaon physics: $K \rightarrow \pi \nu \nu$

Next generation experiments should measure these decays for the 1st time
- $K^+ \rightarrow \pi^+ \nu \nu$ (NA62, CERN)
- $K^0 \rightarrow \pi^0 \nu \nu$ (K0T0, J-PARC)
- Proposals also at FNAL
Data from 2014 commissioning run

Physics data taking starts 2015

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KOTO at JPARC
Data taking May 2013, ended by radiation incident

Allows first results & detailed background studies

Data taking restarted April 2015, expect large improvement with 2015 data

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**Summary of **

#BG inside the signal box

<table>
<thead>
<tr>
<th>BG source</th>
<th>#BG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hadron interaction events</td>
<td>0.18±0.15</td>
</tr>
<tr>
<td>Kaon decay events</td>
<td>0.11±0.04</td>
</tr>
<tr>
<td>Upstream events</td>
<td>0.06±0.06</td>
</tr>
<tr>
<td><strong>Sum</strong></td>
<td>0.36±0.16</td>
</tr>
</tbody>
</table>

• Sensitivity of the 1st physics run = $1.29 \times 10^{-8}$

(c.f) S.E.S. of KEK E391a: $1.11 \times 10^{-8}$

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Observed 1 event in the box (consistent with BG expectation)
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

- We will have a 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)