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
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
The GIM mechanism

\[ K^+ \rightarrow \mu^+ \nu_\mu \& \pi^0 \mu^+ \nu_\mu \] so why not \[ K^0 \rightarrow \mu^+ \mu^- \& \pi^0 \mu^+ \mu^- \]?

- GIM (Glashow, Iliopoulos, Maiani) mechanism (1970)
  - no tree level flavour changing neutral currents
  - suppression of FCNC via loops
- Requires that quarks come in pairs (predicting charm)

\[
A = V_{us} V_{ud}^* f(m_u/m_W) + V_{cs} V_{cd}^* f(m_c/m_W)
\]

2x2 unitarity: \[ V_{us} V_{ud}^* + V_{cs} V_{cd}^* = 0 \]

\[ m_u, m_c < m_W \therefore f(m_u/m_W) \sim f(m_c/m_W) \therefore A \sim 0 \]

kaon mixing \(\Rightarrow\) predict \(m_c\)

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Discovery of charm

- $J$ (Ting; BNL)/$\psi$ (Richter, SLAC) discovery, 1974
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, true in most common models
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
MEG results

$B(\mu^+ \rightarrow e^+ \gamma) < 5.7 \times 10^{-13} @ 90\% \text{ CL}$

arXiv:1303.0754
Prospects for Lepton Flavour Violation

- MEG still taking data; and a further upgrade is planned
- New generations of $\mu - e$ conversion experiments
  - COMET at J-PARC, followed by PRISM/PRIME
  - $\mu 2e$ 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 & potential $\tau$-charm factories
  - $O(100)$ improvements in luminosity $\rightarrow O(10) - O(100)$ improvements in sensitivity (depending on background)
  - LHC experiments have some potential to improve $\tau \rightarrow \mu \mu \mu$

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Neutral meson oscillations

- We have flavour eigenstates $M^0$ and $\bar{M}^0$
  - $M^0$ can be $K^0$ (s$d$), $D^0$ (c$u$), $B^0_d$ (b$d$) or $B^0_s$ (b$s$)
- These can mix into each other
  - via short-distance or long-distance processes
- **Time-dependent Schrödinger eqn.**
  \[
i \frac{\partial}{\partial t} \begin{pmatrix} M^0 \\ \bar{M}^0 \end{pmatrix} = H \begin{pmatrix} M^0 \\ \bar{M}^0 \end{pmatrix} = \begin{pmatrix} M - \frac{i}{2} \Gamma \end{pmatrix} \begin{pmatrix} M^0 \\ \bar{M}^0 \end{pmatrix}
  \]
  - $H$ is Hamiltonian; $M$ and $\Gamma$ are 2x2 Hermitian matrices
- **CPT theorem:** $M_{11} = M_{22}$ & $\Gamma_{11} = \Gamma_{22}$

Particle and antiparticle have equal masses and lifetimes

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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 \( |p|^2 + |q|^2 = 1 \)

label as either S,L (short-, long-lived) or L,H (light, heavy) depending on values of \( \Delta m \) & \( \Delta \Gamma \)

\( \Delta \Gamma = \Gamma_S - \Gamma_L \)

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

- Eigenvalues

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

\[ \Delta m = m_L - m_S \]

\[ \Delta \Gamma = \Gamma_S - \Gamma_L \]

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

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

\[ (q/p)^2 = (M_{12}^* - \frac{1}{2}i\Gamma_{12}^*)/(M_{12} - \frac{1}{2}i\Gamma_{12}) \]
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 
    \[ \frac{\Delta m_d}{\Delta m_s} = \frac{m_{B_d} f_{B_d}^2 \hat{B}_{B_d}}{m_{B_s} f_{B_s}^2 \hat{B}_{B_s}} \frac{|V_{td}|^2}{|V_{ts}|^2} \]

- $\Delta \Gamma$: 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 $|q/p| \neq 1$
    \[ \epsilon = \frac{p-q}{p+q} \neq 0 \]
Simplistic picture of mixing parameters

|       | $\Delta m$ (x = $\Delta m/\Gamma$) | $\Delta \Gamma$ (y = $\Delta \Gamma/(2\Gamma)$) | $|q/p|$ (a$_s$ $\approx 1 - |q/p|^2$) |
|-------|-----------------------------------|-----------------------------------------------|----------------------------------|
| $K^0$ | large                             | $\sim$ maximal                                | small                           |
|       | $\sim$ 500                        | $\sim$ 1                                      | $(3.32 \pm 0.06) \times 10^{-3}$ |
| $D^0$ | small                             | small                                         | small                           |
|       | $(0.63 \pm 0.19)\%$              | $(0.75 \pm 0.12)\%$                          | $0.52^{+0.19}_{-0.24}$          |
| $B^0$ | medium                            | small                                         | small                           |
|       | $0.770 \pm 0.008$                 | $0.008 \pm 0.009$                             | $-0.0003 \pm 0.0021$            |
| $B_s^0$ | large                           | medium                                        | small                           |
|       | $26.49 \pm 0.29$                 | $0.075 \pm 0.010$                             | $-0.0109 \pm 0.0040$            |

- 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

\[ A_{SM}^{AF=2} \approx \frac{G_F^2 m_t^2}{16\pi^2} (V_{ti}V_{tj})^2 \times \langle M | (\bar{Q}_L i \gamma^\mu Q_L) | M \rangle \times F \left( \frac{M_W^2}{m_t^2} \right) \]

- Express NP as perturbation to the SM Lagrangian
  - couplings $c_i$ and scale $\Lambda > m_W$

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

- For example, SM like (left-handed) operators

\[ \Delta \mathcal{L}^{AF=2} = \sum_{i \neq j} \frac{c_{ij}}{\Lambda^2} (\bar{Q}_L i \gamma^\mu Q_L)^2 \]
### Constraints on NP from mixing

<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>
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<tr>
<td></td>
<td>Re</td>
<td>Im</td>
<td>Re</td>
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<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>
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<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>
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<td>$(\bar{c}_L \gamma^\mu u_L)^2$</td>
<td>$1.2 \times 10^3$</td>
<td>$2.9 \times 10^3$</td>
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<td>$(\bar{c}_R u_L)(\bar{c}_L u_R)$</td>
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<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>
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<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>
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<tr>
<td>$(\bar{b}_L \gamma^\mu s_L)^2$</td>
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<td></td>
<td>$7.6 \times 10^{-5}$</td>
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<tr>
<td>$(\bar{b}_R s_L)(\bar{b}_L s_R)$</td>
<td>$3.7 \times 10^2$</td>
<td></td>
<td>$1.3 \times 10^{-5}$</td>
</tr>
</tbody>
</table>
Similar story – but including more (& more up-to-date) inputs, and in pictures

arXiv:1203.0238

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Flavour & CPV
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
What do we know about heavy quark flavour physics as of today?
CKM Matrix : parametrizations

- Many different possible choices of 4 parameters
- PDG: 3 mixing angles and 1 phase

\[ V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & s_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{13}e^{-i\delta} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \]

- Apparent hierarchy: \( s_{12} \sim 0.2, s_{23} \sim 0.04, s_{13} \sim 0.004 \)
  - Wolfenstein parametrization (expansion parameter \( \lambda \sim \sin \theta_c \sim 0.22 \))

\[ V = \begin{pmatrix} 1 - \frac{1}{2} \lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \frac{1}{2} \lambda^2 & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4) \]

- Other choices, eg. based on CP violating phases

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Hierarchy in quark mixing

$$V = \begin{pmatrix}
1 - \frac{1}{2} \lambda^2 & \frac{\lambda}{A} & A \lambda^3 (\rho - i \eta) \\
-\lambda & 1 - \frac{1}{2} \lambda^2 & A \lambda^2 \\
A \lambda^3 (1 - \rho - i \eta) & -A \lambda^2 & 1
\end{pmatrix} + \mathcal{O}(\lambda^4)$$

Very suggestive pattern
No known underlying reason
Situation for leptons (vs) is completely different
Unitarity Tests

- The CKM matrix must be unitary

\[ V_{CKM}^+ V_{CKM} = V_{CKM} V_{CKM}^+ = 1 \]

- Provides numerous tests of constraints between independent observables, such as

\[ |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1 \]
\[ V_{ud} V_{ub}^* + V_{cd} V_{cb}^* + V_{td} V_{tb}^* = 0 \]
CKM Matrix – Magnitudes

\[
\begin{pmatrix}
0.97425 \pm 0.00022 \\
0.2252 \pm 0.0009 \\
0.230 \pm 0.011 \\
0.2252 \pm 0.0009 \\
1.023 \pm 0.036 \\
(8.4 \pm 0.6) \times 10^{-3} \\
(38.7 \pm 2.1) \times 10^{-3} \\
(8.4 \pm 0.6) \times 10^{-3} \\
(38.7 \pm 2.1) \times 10^{-3} \\
0.2252 \pm 0.0009 \\
0.88 \pm 0.07 \\
(3.89 \pm 0.44) \times 10^{-3} \\
(40.6 \pm 1.3) \times 10^{-3}
\end{pmatrix}
\]

superallowed $0^+ \to 0^+ \beta$ decays
semileptonic / leptonic kaon decays
hadronic tau decays
semileptonic / leptonic B decays

semileptonic charm decays
charm production in neutrino beams

$B_d$ oscillations
semileptonic / leptonic charm decays

$B_s$ oscillations
semileptonic / leptonic charm decays

PDG 2010

theory inputs (eg., lattice calculations) required
The Unitarity Triangle

$$V_{ud} V_{ub}^* + V_{cd} V_{cb}^* + V_{td} V_{tb}^* = 0$$

Three complex numbers add to zero
⇒ triangle in Argand plane

Axes are $\bar{\rho}$ and $\bar{\eta}$ where

$$\bar{\rho} + i \bar{\eta} = -\frac{V_{ud} V_{ub}^*}{V_{cd} V_{cb}^*}$$

$$\rho + i \eta = \frac{\sqrt{1 - A^2 \lambda^4 (\bar{\rho} + i \bar{\eta})}}{\sqrt{1 - \lambda^2 [1 - A^2 \lambda^4 (\bar{\rho} + i \bar{\eta})]}}$$

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Predictive nature of KM mechanism

In the Standard Model the KM phase is the sole origin of CP violation

Hence:
all measurements must agree on the position of the apex of the Unitarity Triangle

(Illustration shown assumes no experimental or theoretical uncertainties)
Time-Dependent CP Violation in the $B^0 - \bar{B}^0$ System

- For a $B$ meson known to be 1) $B^0$ or 2) $\bar{B}^0$ at time $t=0$, then at later time $t$:

\[
\Gamma (B^0_{phys} \rightarrow f_{CP}(t)) \propto e^{-\Gamma t} \left| 1 - (S \sin(\Delta m t) - C \cos(\Delta m t)) \right|
\]
\[
\Gamma (\bar{B}^0_{phys} \rightarrow f_{CP}(t)) \propto e^{-\Gamma t} \left| 1 + (S \sin(\Delta m t) - C \cos(\Delta m t)) \right|
\]

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

\[
S = \frac{2 \Im(\lambda_{CP})}{1 + |\lambda_{CP}^2|} \quad C = \frac{1 - |\lambda_{CP}^2|}{1 + |\lambda_{CP}^2|} \quad \lambda_{CP} = \frac{q \bar{A}}{p \ A}
\]

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

NPB 193 (1981) 85
Categories of CP violation

- Consider decay of neutral particle to a CP eigenstate

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

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

- \( |\frac{\overline{A}}{A}| \neq 1 \) (CP violation in decay (direct CPV))

- \( \Im \left( \frac{q}{p} \frac{\overline{A}}{A} \right) \neq 0 \) (CP violation in interference between mixing and decay)
Asymmetric B factory principle

To measure $t$ require B meson to be moving
  $\rightarrow e^+e^-$ at threshold with asymmetric collisions (Oddone)

Other possibilities considered
  $\rightarrow$ fixed target production?
  $\rightarrow$ hadron collider?
  $\rightarrow$ $e^+e^-$ at high energy?

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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⁺

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B factories – world record luminosities

~ 433/fb on Y(4S)

~ 711/fb on Y(4S)

Total over $10^9$ $B\bar{B}$ pairs recorded
World record luminosities (2)
BaBar Detector

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

- **1.5 T solenoid**

- **EMC**
  - 6580 CsI(Tl) crystals

- **Drift Chamber**
  - 40 stereo layers

- **Silicon Vertex Tracker**
  - 5 layers, double sided strips

- **e^+ (3.1 GeV)**

- **e^- (9 GeV)**

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

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Belle Detector

- SC solenoid 1.5T
- CsI(Tl) $16X_0$
- TOF counter
- Aerogel Cherenkov cnt. $n=1.015\sim1.030$
- 3.5 GeV $e^+$
- 8 GeV $e^-$
- Central Drift Chamber small cell +He/C$_2$H$_6$
- Si vtx. det.
  - 3 lyr. DSSD
  - 4 lyr. since summer 2003
- $\mu$ / $K_L$ detection
  - 14/15 lyr. RPC+Fe

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Results for the golden mode

\[ B^0 \rightarrow J/\psi K^0 \]

**BABAR**

\[ \eta_f = -1 \]

\[ \eta_f = +1 \]

**BELLE**

**PRD 79 (2009) 072009**

**PRL 108 (2012) 171802**
Compilation of results

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

Everything is here

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Reference</th>
<th>Value</th>
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<tbody>
<tr>
<td>BaBar</td>
<td>PRD 79 (2009); 072009</td>
<td>0.69 ± 0.03 ± 0.01</td>
</tr>
<tr>
<td>BaBar ( \chi_{2}, K_{S} )</td>
<td>PRD 80 (2009); 112001</td>
<td>0.69 ± 0.52 ± 0.04 ± 0.07</td>
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<tr>
<td>BaBar ( J/\psi ) (hadronic) ( K_{S} )</td>
<td>PRD 69 (2004); 052001</td>
<td>1.56 ± 0.42 ± 0.21</td>
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<td>Belle</td>
<td>PRL 108 (2012); 171802</td>
<td>0.67 ± 0.02 ± 0.01</td>
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<tr>
<td>ALEPH</td>
<td>PLB 492, 259 (2000)</td>
<td>0.84^{+0.82}_{-1.04} ± 0.16</td>
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<td>OPAL</td>
<td>EPJ C5, 379 (1998)</td>
<td>3.20^{+1.80}_{-2.00} ± 0.50</td>
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<td>CDF</td>
<td>PRD 61, 072005 (2000)</td>
<td>0.79^{+0.41}_{-0.44}</td>
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<tr>
<td>LHCb</td>
<td>LHCb-CONF-2011-004</td>
<td>0.53^{+0.28}_{-0.26} ± 0.05</td>
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<tr>
<td>Belle5S</td>
<td>PRL 108 (2012); 171801</td>
<td>0.57 ± 0.58 ± 0.06</td>
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<tr>
<td>Average</td>
<td>HFAQ</td>
<td>0.68 ± 0.02</td>
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Compilation of results

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

<table>
<thead>
<tr>
<th></th>
<th>Average</th>
<th>LHCb result using J/ψ K_s not included</th>
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</thead>
<tbody>
<tr>
<td>( J/\psi \ K_s )</td>
<td>0.665 ± 0.024</td>
<td>0.73 ± 0.07 ± 0.04</td>
</tr>
<tr>
<td>( J/\psi \ K_L )</td>
<td>0.663 ± 0.041</td>
<td></td>
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<tr>
<td>( \psi(2S) \ K_s )</td>
<td>0.807 ± 0.067</td>
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<tr>
<td>( \chi_{c1} \ K_s )</td>
<td>0.632 ± 0.099</td>
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$R_t$ side from $B^0 - B^0$ mixing

$$R_t = \left| \frac{V_{td}}{V_{cd}} \right| \frac{V_{tb}^*}{V_{cb}^*} \quad \& \quad \frac{\Delta m_d}{\Delta m_s} = \frac{m_{B_d} f_{B_d}^2 \hat{B}_{B_d}}{m_{B_s} f_{B_s}^2 \hat{B}_{B_s}} \left| \frac{V_{td}}{V_{ts}} \right|^2$$

World average based on many measurements

$P(\Delta t) = (1 \pm \cos(\Delta m \Delta t)) e^{i\Delta t}/2\tau$

$\Delta m_d = (0.511 \pm 0.005 \pm 0.006) \text{ ps}^{-1}$

PRD 71, 072003 (2005)

$\Delta m_s = (17.77 \pm 0.10 \pm 0.07) \text{ ps}^{-1}$

PRL 97, 242003 (2006)

$\left| \frac{V_{td}}{V_{ts}} \right| = 0.211 \pm 0.001 \pm 0.005$

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$R_t$ side from $B^0 - B^0$ mixing

$$R_t = \left| \frac{V_{td} V_{tb}^*}{V_{cd} V_{cb}^*} \right|$$

$$\frac{\Delta m_d}{\Delta m_s} = \frac{m_{B_d} f_{B_d}^2 \frac{\Lambda}{B_{B_d}}} {m_{B_s} f_{B_s}^2 \frac{\Lambda}{B_{B_s}}} \left| \frac{V_{td}}{V_{ts}} \right|^2$$

World average based on many measurements

$P(\Delta t) = (1 \pm \cos(\Delta m \Delta t)) e^{i|\Delta t|/2\tau}$

$\Delta m_d = (0.511 \pm 0.005 \pm 0.006) \text{ ps}^{-1}$

$\Delta m_s = (17.768 \pm 0.023 \pm 0.006) \text{ ps}^{-1}$

PRD 71, 072003 (2005)

NJP 15 (2013) 053021

$\left| \frac{V_{td}}{V_{ts}} \right| = 0.211 \pm 0.001 \pm 0.005$

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\[ R_u = \left| \frac{V_{ud} V_{ub}^*}{V_{cd} V_{cb}^*} \right| \]

\textbf{Approaches:}

- **exclusive semileptonic B decays**, eg. \( B^0 \rightarrow \pi^- e^+ \nu \)
  - require knowledge of form factors
  - can be calculated in lattice QCD at kinematical limit

- **inclusive semileptonic B decays**, eg. \( B \rightarrow X_u e^+ \nu \)
  - clean theory, based on Operator Product Expansion
  - experimentally challenging:
    - need to reject \( b \rightarrow c \) background
    - cuts re-introduce theoretical uncertainties
\[ |V_{ub}| \text{ from exclusive semileptonic decays} \]

Current best measurements use \( B^0 \to \pi^- l^+ \nu \)

BaBar experiment
PRD 83 (2011) 052011
PRD 83 (2011) 032007

Belle experiment
PRD 83 (2011) 071101(R)

\[ |V_{ub}| = (3.09 \pm 0.08 \pm 0.12 \pm 0.08 \pm 0.12 \times 10^{-3} \]

lattice uncertainty

\[ |V_{ub}| = (3.43 \pm 0.33) \times 10^{-3} \]

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$|V_{ub}|$ from inclusive semileptonic decays

- Main difficulty to measure inclusive $B \to X_u l^+ \nu$
  - background from $B \to X_c l^+ \nu$

- Approaches
  - cut on $E_l$ (lepton endpoint), $q^2$ ($l\nu$ invariant mass squared), $M(X_u)$, or some combination thereof

- Example: endpoint analysis

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|\[V_{ub} \text{ }|\text{ inclusive - compilation}\]

Different theoretical approaches (2 of 4 used by HFAG)

<table>
<thead>
<tr>
<th>Theory</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLEO (E^3)</td>
<td>3.83 ± 0.45 + 0.32 - 0.33</td>
</tr>
<tr>
<td>BELLE sin. ann. (m_\tau, q^*)</td>
<td>4.23 ± 0.45 + 0.29 - 0.30</td>
</tr>
<tr>
<td>BELLE (E^3)</td>
<td>4.64 ± 0.43 + 0.29 - 0.31</td>
</tr>
<tr>
<td>BABAR (E^3)</td>
<td>4.18 ± 0.24 + 0.29 - 0.31</td>
</tr>
<tr>
<td>BABAR (E_\mu, \xi^\mu)</td>
<td>4.28 ± 0.29 + 0.36 - 0.37</td>
</tr>
<tr>
<td>BELLE (m_\tau)</td>
<td>3.90 ± 0.26 + 0.24 - 0.26</td>
</tr>
<tr>
<td>BABAR (m_\tau)</td>
<td>4.02 ± 0.19 + 0.27 - 0.29</td>
</tr>
<tr>
<td>BABAR (m_\tau, q^*)</td>
<td>4.32 ± 0.28 + 0.29 - 0.31</td>
</tr>
<tr>
<td>BABAR (P^+)</td>
<td>3.65 ± 0.24 + 0.25 - 0.37</td>
</tr>
</tbody>
</table>

Average +/- exp + theory - theory
4.06 ± 0.15 + 0.25 - 0.37

\(\chi^2/\text{dof} = 13.08 \, (\text{CL} = 99.00 \%)\)

Brod, Leung, Nueburt and Piz (BLNP)

\(\chi^2/\text{dof} = 7.17 \, (\text{CL} = 52.00 \%)\)
Anderson and Gersa (DGE)
JHEP 0601:097, 2006
E. Gersa at X04 0803.4524

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\[ |V_{ub}| \text{ average} \]

- Averages on \(|V_{ub}|\) from both exclusive and inclusive approaches
  - exclusive: \(|V_{ub}| = (3.23 \pm 0.31) \times 10^{-3} \)
  - inclusive: \(|V_{ub}| = (4.41 \pm 0.22) \times 10^{-3} \)
  - slight tension between these results
  - in both cases theoretical errors are dominant
    - but some “theory” errors can be improved with more data
  - PDG2012 does naïve average rescaling due to inconsistency to obtain \(|V_{ub}| = (4.15 \pm 0.49) \times 10^{-3} \)
Partial summary

Adding a few other constraints we find

\[ \rho = 0.132 \pm 0.020 \]
\[ \eta = 0.358 \pm 0.012 \]

Consistent with Standard Model fit
- some “tensions”

Still plenty of room for new physics
Measurement of $\alpha$

- Similar analysis using $b \rightarrow u\bar{u}d$ decays (e.g. $B_d^0 \rightarrow \pi^+\pi^-$) probes $\pi-(\beta+\gamma) = \alpha$
  - but $b \rightarrow du\bar{u}$ penguin transitions contribute to same final states ⇒ “penguin pollution”
  - $C \neq 0 \leftrightarrow$ direct CP violation can occur
  - $S \neq +\eta_{CP} \sin(2\alpha)$

- Two approaches (optimal approach combines both)
  - try to use modes with small penguin contribution
  - correct for penguin effect (isospin analysis)

PRL 65 (1990) 3381
Experimental Situation

\( \pi^+ \pi^- S_{CP} \text{ vs } C_{CP} \)

- Large CP violation
- Large penguin effect

\( \rho^+ \rho^- S_{CP} \text{ vs } C_{CP} \)

- Small CP violation
- Small penguin effect

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improved measurements needed!
Measurement of $\alpha$

$\alpha = (89.0^{+4.4}_{-4.2})^\circ$

Is there any physical significance in the fact that $\alpha \approx 90^\circ$?