CKMfitter keynote (well, beamer... ) talk

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Fundamental parameters from Lattice QCD
31 August 2015
The name of the game
Why flavour?

\[ \mathcal{L}_{SM} = \mathcal{L}_{gauge}(A_a, \psi_j) + \mathcal{L}_{Higgs}(\phi, A_a, \psi_j) \]

**Gauge part** \( \mathcal{L}_{gauge}(A_a, \psi_j) \)
- Highly symmetric (gauge symmetry, \textit{flavour symmetry})
- Well-tested experimentally (electroweak precision tests)
- Stable with respect to quantum corrections

**Higgs part** \( \mathcal{L}_{Higgs}(\phi, A_a, \psi_j) \)
- Ad hoc potential
- Dynamics not fully tested (more room for NP)
- Not stable w.r.t quantum corrections
- Origin of \textit{flavour structure} of the Standard Model

Flavour structure: Quark masses and CKM matrix from diagonalisation of Yukawa couplings after EWSB
Important, unexplained hierarchy among 10 of 19 params of SM $m_\nu=0$

- Mass (6 params, a lot of small ratios of scales)
- CP violation (4 params, strong hierarchy between generations)

With interesting phenomenological consequences

- Hierarchy of CP asymmetries according to generations
- Quantum sensitivity (via loops) to large range of scales
- GIM suppression of Flavour-Changing Neutral Currents
- Potential to unravel patterns of deviations from NP (in a time where direct searches have not succeeded)
The CKM matrix

In SM, flavour dynamics related to weak charged transitions which mix quarks of different generations

Encoded in unitary CKM matrix

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

3 generations \(\implies\) 1 phase, only source of \(C\!P\)-violation in SM

Wolfenstein parametrisation, defined to hold to all orders in \(\lambda\) and rephasing invariant

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

\[\lambda^2 = \frac{|V_{us}|^2}{|V_{ud}|^2 + |V_{us}|^2}\]

\[A^2\lambda^4 = \frac{|V_{cb}|^2}{|V_{ud}|^2 + |V_{us}|^2}\]

\[\Rightarrow\] 4 parameters describing the CKM matrix
Extracting the CKM parameters

- CP-invariance of QCD to build hadronic-indep. CP-violating asym. or to determine hadronic inputs from data
- Statistical framework to combine data and assess uncertainties

\[ V = \begin{pmatrix}
  u & n & e^- & \bar{\nu} \\
  c & D & \ell^- & \bar{\nu} \\
  t & B^0 & B_s & \ell^- \bar{\nu}
\end{pmatrix} \]

<table>
<thead>
<tr>
<th>Exp. uncert.</th>
<th>Theoretical uncertainties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tree</td>
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<tr>
<td>Loop</td>
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<tr>
<td>Loop</td>
<td></td>
</tr>
</tbody>
</table>

- $B(b) \rightarrow D(c)\ell\nu$
- $B(b) \rightarrow \pi(u)\ell\nu$
- $M \rightarrow \ell\nu$
- $\epsilon_K$ (K mixing)
- $\Delta m_d, \Delta m_s$ ($B_d, B_s$ mixings)

- $|V_{cb}|$ vs form factor (OPE)
- $|V_{ub}|$ vs form factor (OPE)
- $|V_{UD}|$ vs $f_M$ (decay cst)
- $(\bar{\rho}, \bar{\eta})$ vs $B_K$ (bag parameter)
- $|V_{tb}V_{tq}|$ vs $f_B^2 B_B$ (bag param)
The inputs

frequentist (\(\sim \chi^2\) minim.) + Rfit scheme for theory uncert.

data = weak \(\otimes\) QCD \(\implies\) Need for hadronic inputs (mostly lattice)

|\(V_{ud}\)| superallowed \(\beta\) decays
|\(V_{us}\)| \(K\ell_3\) (Flavianet)
|\(V_{us}/V_{ud}\)| \(K \rightarrow \ell\nu, \tau \rightarrow K\nu\tau\)
|\(V_{cd}\)| \(D \rightarrow \mu\nu, D \rightarrow \pi\ell\nu\)
|\(V_{cs}\)| \(D_s \rightarrow \mu\nu, D_s \rightarrow \tau\nu, D \rightarrow \pi\ell\nu\)
|\(V_{ub}\)| inclusive and exclusive \(B\) semileptonic
|\(V_{cb}\)| inclusive and exclusive \(B\) semileptonic
|\(B \rightarrow \tau\nu\)| \((1.24 \pm 0.22) \cdot 10^{-4}\)

|\(V_{ub}/V_{cb}\)| \(\Lambda_b\) semileptonic decays
|\(\Delta m_d\)| last WA \(B_d - \bar{B}_d\) mixing
|\(\Delta m_s\)| last WA \(B_s - \bar{B}_s\) mixing
|\(\beta\)| last WA \(J/\psi K(\ast)\)
|\(\alpha\)| last WA \(\pi\pi, \rho\pi, \rho\rho\)
|\(\gamma\)| last WA \(B \rightarrow D(\ast)K(\ast)\)

PRC79, 055502 (2009)

\(f_+(0) = 0.9645 \pm 0.0015 \pm 0.0045\)
\(f_K = 155.2 \pm 0.2 \pm 0.6\) MeV
\(f_K/f_\pi = 1.1952 \pm 0.0007 \pm 0.0029\)
\(\hat{B}_K = 0.7615 \pm 0.0027 \pm 0.0137\)
\(f_{D_s}/f_D = 1.175 \pm 0.001 \pm 0.004, f_{D \rightarrow \pi(0)}\)
\(f_{D_s} = 248.2 \pm 0.3 \pm 1.9\) MeV, \(f_{D \rightarrow K(0)}\)
|\(V_{ub}\)| \(\cdot 10^3 = 4.01 \pm 0.08 \pm 0.22\)
|\(V_{cb}\)| \(\cdot 10^3 = 41.00 \pm 0.33 \pm 0.74\)
\(f_{B_s}/f_{B_d} = 1.205 \pm 0.003 \pm 0.006\)
\(f_{B_s} = 224.0 \pm 1.0 \pm 2.0\) MeV
\(B_{B_s}/B_{B_d} = 1.023 \pm 0.013 \pm 0.014\)
\(B_{B_s} = 1.320 \pm 0.016 \pm 0.030\)

isospin

GLW/ADS/GGSZ

as well as \(m_t, m_c, \alpha_s(M_Z)\)!
Statistical framework

\[ q = (A, \lambda, \bar{\rho}, \bar{\eta} \ldots) \] to be determined

- \( \mathcal{O}_{\text{meas}} \pm \sigma_{\mathcal{O}} \) experimental values of observables
- \( \mathcal{O}_{\text{th}}(q) \) theoretical description in a given model

In case of statistical uncertainties \( \sigma_{\mathcal{O}} \), likelihoods and \( \chi^2 \)

\[
\mathcal{L}(q) = \prod_{\mathcal{O}} \mathcal{L}_{\mathcal{O}}(q) \\
\chi^2(q) = -2 \ln \mathcal{L}(q) = \sum_{\mathcal{O}} \left( \frac{\mathcal{O}_{\text{th}}(q) - \mathcal{O}_{\text{meas}}}{\sigma_{\mathcal{O}}} \right)^2
\]

- Central value: estimator \( \hat{q} \) max likelihood: \( \chi^2(\hat{q}) = \min_q \chi^2(q) \)
- Range: confidence level for each \( q_0 \) (\( p \)-value for \( q = q_0 \)) by:

\[
\Delta \chi^2(q_0) = \chi^2(q_0) - \min_q \chi^2(q)
\]

assumed to obey \( \chi^2 \) law with \( N = \text{dim}(q) \) to yield CIs

- Pull: comparison of \( \chi^2_{\min} \) with and without one measurement

\[
p_{\mathcal{O}} = \sqrt{\min_q \chi^2_{\text{with meas}}(q) - \min_q \chi^2_{\text{without meas}}(q)}
\]
Rfit scheme

: Treatment of systematics within the Rfit scheme

- modify likelihood $\mathcal{L} = \exp(-\chi^2/2)$ to get a $\chi^2$ with flat bottom (syst) and parabolic walls (stat)
- all values within range of syst treated on the same footing

[More in Jérôme Charles’ talk on Wednesday]
Averaging lattice results

Collecting lattice results
- follow FLAG to exclude limited results
- supplement with more recent published results with error budget

Splitting error estimates into stat and syst
- Stat: essentially related to size of gauge conf
- Syst: fermion action, $a \to 0$, $L \to \infty$, mass extrapolations...
  - added linearly using error budget

“Educated Rfit” used to combine the results
- no correlations assumed
- product of (Gaussian + Rfit) likelihoods for central value
- product of Gaussian (stat) likelihoods for stat uncertainty
- syst uncertainty of the combination = most precise method
  - the present state of art cannot allow us to reach a better theoretical accuracy than the best of all estimates
  - best estimate should not be penalized by less precise methods
Illustration for $f_K/f_\pi$

<table>
<thead>
<tr>
<th>Reference</th>
<th>$N_f$</th>
<th>Mean</th>
<th>Stat</th>
<th>Syst</th>
</tr>
</thead>
<tbody>
<tr>
<td>ETMC09</td>
<td>2</td>
<td>1.210</td>
<td>0.006</td>
<td>0.024</td>
</tr>
<tr>
<td>HPQCD/UKQCD07</td>
<td>2+1</td>
<td>1.189</td>
<td>0.002</td>
<td>0.014</td>
</tr>
<tr>
<td>MILC10</td>
<td>2+1</td>
<td>1.197</td>
<td>0.002</td>
<td></td>
</tr>
<tr>
<td>BMW10</td>
<td>2+1</td>
<td>1.192</td>
<td>0.007</td>
<td>0.013</td>
</tr>
<tr>
<td>LVdW11</td>
<td>2+1</td>
<td>1.202</td>
<td>0.011</td>
<td>0.024</td>
</tr>
<tr>
<td>RBC-UKQCD12</td>
<td>2+1</td>
<td>1.1991</td>
<td>0.0116</td>
<td>0.0185</td>
</tr>
<tr>
<td>HPQCD13</td>
<td>2+1+1</td>
<td>1.1938</td>
<td>0.0015</td>
<td>0.0032</td>
</tr>
<tr>
<td>FNAL-MILC14</td>
<td>2+1+1</td>
<td>1.1956</td>
<td>0.0010</td>
<td></td>
</tr>
<tr>
<td>ETMC14</td>
<td>2+1+1</td>
<td>1.188</td>
<td>0.011</td>
<td>0.020</td>
</tr>
</tbody>
</table>

Our average 1.1952 0.0007 0.0029

- Other values proposed: $1.194 \pm 0.005 (N_f = 2 \text{ FLAG}),$
  $1.192 \pm 0.005 (N_f = 3 \text{ FLAG})$...

- Results for QCD decay constants (further corrections in BRs)
- Used for decay constants, bag parameters, form factors...
- Some assumptions on correlations for $B_{Bs}$ and $B_{B_d}/B_{Bs}$ since some collaborations quote only $f_B\sqrt{B}$
Two decades of CKM

[LEP, KTeV, NA48, Babar, Belle, CDF, DØ, LHCb, CMS…]

1995

2001

2004

2006

2009

2015

S. Descotes-Genon (LPT-Orsay)

CKMfitter

MITP15 - 31/8/15
Where we are now
\[ \epsilon_K = 0.150^{+0.012}_{-0.006} \]
\[ \lambda = 0.2254^{+0.0004}_{-0.0003} \]
\[ \bar{\rho} = 0.150^{+0.012}_{-0.006} \]
\[ \bar{\eta} = 0.354^{+0.007}_{-0.008} \]

(68% CL)
Consistency of the KM mechanism

Validity of Kobayashi-Maskawa picture of $CP$ violation
PULLS

- Pulls for various observables (included in the fit or not)
- For 1D, pull \( \text{obs} = \sqrt{\chi^2_{\text{min}}}; \) with \( \text{obs} - \chi^2_{\text{min}}; \) w/o obs
- If Gaussian errors, uncorrelated, random vars of mean 0 and variance 1
- Here correlations, and some pulls = 0 due to the Rfit model for syst

<table>
<thead>
<tr>
<th>Observable</th>
<th>Pull (σ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( B_{s} \rightarrow \mu \mu )</td>
<td>0.91</td>
</tr>
<tr>
<td>( \phi_s )</td>
<td>0.65</td>
</tr>
<tr>
<td>( \gamma )</td>
<td>0.91</td>
</tr>
<tr>
<td>( \alpha )</td>
<td>0.84</td>
</tr>
<tr>
<td>( \sin 2\beta )</td>
<td>1.66</td>
</tr>
<tr>
<td>( c_K )</td>
<td>0.05</td>
</tr>
<tr>
<td>( \Delta m_s )</td>
<td>1.21</td>
</tr>
<tr>
<td>( \Delta m_d )</td>
<td>1.29</td>
</tr>
<tr>
<td>( B(D \rightarrow \tau \nu) )</td>
<td>1.22</td>
</tr>
<tr>
<td>(</td>
<td>V_{ub}</td>
</tr>
<tr>
<td>(</td>
<td>V_{cb}</td>
</tr>
<tr>
<td>( B(D \rightarrow \mu \nu) )</td>
<td>1.83</td>
</tr>
<tr>
<td>( B(D \rightarrow \mu \nu) )</td>
<td>1.08</td>
</tr>
<tr>
<td>( B(D \rightarrow \tau \nu) )</td>
<td>1.64</td>
</tr>
<tr>
<td>( B(D \rightarrow \pi \nu) )</td>
<td>0.01</td>
</tr>
<tr>
<td>(</td>
<td>V_{cs}</td>
</tr>
<tr>
<td>(</td>
<td>V_{cd}</td>
</tr>
<tr>
<td>( B(K_{s0}) )</td>
<td>2.22</td>
</tr>
<tr>
<td>( B(K_{e0}) )</td>
<td>0.03</td>
</tr>
<tr>
<td>( B(K_{e3}) )</td>
<td>1.44</td>
</tr>
<tr>
<td>( B(K_{e3}) )</td>
<td>0.00</td>
</tr>
<tr>
<td>(</td>
<td>V_{ud}</td>
</tr>
</tbody>
</table>

No indication of significant deviations from CKM picture
$|V_{ub}|$ from semileptonic $B$ decays

Two ways of getting $|V_{ub}|$:
- Inclusive: $b \to u \ell \nu + \text{Operator Product Expansion}$
- Exclusive: $B \to \pi \ell \nu + \text{Form factors}

$|V_{ub}|_{inc} = 4.45 \pm 0.18 \pm 0.31$
$|V_{ub}|_{exc} = 3.72 \pm 0.09 \pm 0.22$

$|V_{ub}|_{ave} = 4.01 \pm 0.08 \pm 0.22$

with all values $\times 10^{-3}$

- HFAG, with theory errors added linearly
- systematics combined using Educated Rfit

Indirect det. from global fit: $|V_{ub}|_{fit} = 3.57^{+0.15}_{-0.14} (4\%)$
Two ways of getting $|V_{cb}|$:

- Inclusive: $b \to c \ell \nu + \text{OPE for moments}$
- Exclusive: $B \to D(\ast) \ell \nu + \text{Form factors}$

$|V_{cb}|_{\text{inc}} = 42.42 \pm 0.44 \pm 0.74$

$|V_{cb}|_{\text{exc}} = 38.99 \pm 0.49 \pm 1.17$

$|V_{cb}|_{\text{ave}} = 41.00 \pm 0.33 \pm 0.74$

with all values $\times 10^{-3}$

- HFAG, with theory errors added linearly
- Systematics combined using Educated Rfit

Indirect det. from global fit: $|V_{cb}|_{\text{fit}} = 43.0^{+0.4}_{-1.4} (4\%)$
Information on $|V_{ub}|$ from $Br(B \rightarrow \tau \nu)$

New LHCb result on $|V_{ub}/V_{cb}|$ from

$\Gamma(\Lambda_b \rightarrow p\mu\nu)/\Gamma(\Lambda_b \rightarrow \Lambda_c\mu\nu)$ at high $q^2$

[Detmold, Lehner and Meinel]

Global fit favours exclusive $|V_{ub}|_{SL}$ but

inclusive $|V_{cb}|_{SL}$
From 2014 to 2015

- Increase in the average used as input for $|V_{ub}|_{SL}$
- Slight tension between $|V_{ub}|_{SL}$ and $\sin(2\beta)$ (1.5 $\sigma$ for 2D hyp)
- Reducing uncertainty on CKM params (mostly $\bar{\eta}$)

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S. Descotes-Genon (LPT-Orsay)

CKMfitter
\textbf{\textit{\(|V_{ud}|\) and \(|V_{us}|\)}}

- “Direct” (semi- and leptonic) vs “indirect” (other sectors)
- \((|V_{ud}|, |V_{us}|)\): nuclear \(\beta\) + leptonic \(K, \pi\) and \(\tau\) decays
- Same level of accuracy for exp and lattice inputs

\begin{tabular}{ccc}
Leptonic & Semilep & \\
\(|V_{us}|\) & \(|V_{us}/V_{ud}|\) & \(|V_{us}|\) \\
Exp & 0.1\% & 0.1\% & 0.2\% \\
Lattice & 0.4\% & 0.3\% & 0.5\% \\
\end{tabular}

- \(|V_{ud}|\) from superallowed \(\beta\) decays is 10 times more accurate...
**|V_{cd}| and |V_{cs}|**

- **“Direct”** (semi- and leptonic) vs **“indirect”** (other sectors)
- \((|V_{cd}|, |V_{cs}|)\): \(D \rightarrow \pi \ell \nu\), \(D \rightarrow K \ell \nu\), leptonic decays
- Direct constraint mostly from leptonic decays

<table>
<thead>
<tr>
<th></th>
<th>Leptonic</th>
<th>Semileptonic</th>
</tr>
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<tbody>
<tr>
<td>(</td>
<td>V_{cd}</td>
<td>)</td>
</tr>
<tr>
<td>(</td>
<td>V_{cs}</td>
<td>)</td>
</tr>
<tr>
<td>(</td>
<td>V_{cd}</td>
<td>)</td>
</tr>
<tr>
<td>(</td>
<td>V_{cs}</td>
<td>)</td>
</tr>
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*Excluded area has CL > 0.95*
Hadronic inputs from lattice

- Possibility to compare input and fit result (without including the inputs)
- Fit results consistent, but mostly not competitive on accuracy, with lattice results

<table>
<thead>
<tr>
<th></th>
<th>Input</th>
<th>Fit [input not included]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_K$</td>
<td>$155.2 \pm 0.2 \pm 0.6$</td>
<td>$156.5^{+0.1}_{-0.8}$</td>
</tr>
<tr>
<td>$f_K/f_\pi$</td>
<td>$1.194 \pm 0.001 \pm 0.003$</td>
<td>$1.191^{+0.006}_{-0.003}$</td>
</tr>
<tr>
<td>$\hat{B}_K$</td>
<td>$0.762 \pm 0.003 \pm 0.014$</td>
<td>$0.70^{+0.28}_{-0.05}$</td>
</tr>
<tr>
<td>$f_{B_s}$</td>
<td>$225.6 \pm 1.1 \pm 5.4$</td>
<td>$225.9^{+6.4}_{-6.7}$</td>
</tr>
<tr>
<td>$f_{B_s}/f_{B_d}$</td>
<td>$1.205 \pm 0.003 \pm 0.006$</td>
<td>$1.242^{+0.043}_{-0.031}$</td>
</tr>
<tr>
<td>$B_{B_s}$</td>
<td>$1.320 \pm 0.016 \pm 0.030$</td>
<td>$1.313^{+0.094}_{-0.071}$</td>
</tr>
<tr>
<td>$B_{B_s}/B_{B_d}$</td>
<td>$1.023 \pm 0.013 \pm 0.014$</td>
<td>$1.128^{+0.052}_{-0.071}$</td>
</tr>
</tbody>
</table>
\( \bar{\rho}_{B_s} + i \bar{\eta}_{B_s} = -\frac{V_{us} V_{ub}^*}{V_{cs} V_{cb}^*} \)

provides the \( B_s \) Unitarity Triangle \((\lambda^4, \lambda^2, \lambda^2)\)

- Information on \( B_s \) mixing angle \( \beta_s \) from \( B_s \to J/\psi\phi \)
- Not relevant for SM determination of CKM parameters

\[
\bar{\rho}_{B_s} = -0.00805^{+0.00034}_{-0.00065} \\
\bar{\eta}_{B_s} = -0.01897^{+0.00041}_{-0.00036}
\]
FCNC now and in the future
$\Delta F = 1: B_s \to \mu\mu$

- $\Delta F = 1$ FCNC sensitive to pseudo/scalar contributions, measured by LHCb and CMS
- Theoretical progress
  - Inclusion of $B_s$ mixing in experimental time-integrated rate
    $\langle Br(B_s \to \mu\mu) \rangle \simeq 1.1 Br_{t=0}$
  - NLO QCD + LO EW $\to$ NNLO QCD + NLO EW
    [Fleischer et al., Bobeth et al.]

- SM (and MFV) correlation between $Br(B_d \to \mu\mu)$ and $Br(B_s \to \mu\mu)$, driven by $\Delta m_d/\Delta m_s$:
  $Br(B_d \to \mu\mu)_{t=0}/Br(B_s \to \mu\mu)_{t=0} = 0.0298^{+0.0008}_{-0.0010}$

- Further test of pseudo/scalar operators provided by
  $Br(B_d \to \tau\tau)_{t=0} \times 10^8 = 2.05^{+0.13}_{-0.15}$
  $Br(B_s \to \tau\tau)_{t=0} \times 10^7 = 6.98^{+0.38}_{-0.43}$

S. Descotes-Genon (LPT-Orsay)
$\Delta F = 1: K \rightarrow \pi \nu \bar{\nu}$

- $K \rightarrow \pi \nu \bar{\nu}$ rare decays
  - very clean probes of $Z$ penguins and boxes
- $Br(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (0.88^{+0.09}_{-0.10}) \times 10^{-10}$ and
  - $Br(K_L \rightarrow \pi^0 \nu \bar{\nu}) = (0.31^{+0.02}_{-0.02}) \times 10^{-10}$
- NA62 and KOTO expected to provide measurements at 10% accuracy for charged and neutral modes respectively
Neutral-meson mixing described by

\[ i \frac{d}{dt} \left( \begin{pmatrix} B_q(t) \\ \bar{B}_q(t) \end{pmatrix} \right) = \left( M^q - \frac{i}{2} \Gamma^q \right) \left( \begin{pmatrix} B_q(t) \\ \bar{B}_q(t) \end{pmatrix} \right) \]

- Non-hermitian Hamiltonian (only 2 states) but \( M \) and \( \Gamma \) hermitian
- Mixing due to non-diagonal terms \( M^q_{12} - i \Gamma^q_{12}/2 \)

\[ \implies \text{Diagonalisation: physical } |B^q_{H,L}\rangle = p |B_q\rangle \mp q |\bar{B}_q\rangle \]

of masses \( M^q_{H,L} \), widths \( \Gamma^q_{H,L} \)

In terms of \( M^q_{12} \) and \( \Gamma^q_{12} \)

- Mass difference \( \Delta m_q = M^q_H - M^q_L \)
- Width difference \( \Delta \Gamma_q = \Gamma^q_L - \Gamma^q_H \)
- Semileptonic asymmetry \( a^q_{SL} = \frac{\Gamma(\bar{B}_q(t) \to \ell^+ \nu X) - \Gamma(B_q(t) \to \ell^- \nu X)}{\Gamma(\bar{B}_q(t) \to \ell^+ \nu X) + \Gamma(B_q(t) \to \ell^- \nu X)} \)
- Mixing phase in time-dep analysis

Accessible for \( B_d \) and \( B_s \) at Babar, Belle, CDF, DØ, LHCb.
\( \Delta F = 2: \) New Physics potential

**Eff. Hamiltonian integrating out heavy** \( W, Z, t \)

- \( M_{12} \) dominated by (virtual) top boxes
  
  \( M_{q_{12}} = (M_{12})_{SM} \times \Delta_q \)
  
  \( \Delta m_q (\leftrightarrow |\Delta_q|), a_{SL}^q (\leftrightarrow \Delta_q), \Delta \Gamma_q \) and \( \phi_{Bq} (\leftrightarrow \phi_{\Delta q}) \)

- \( \Gamma_{12} \) dominated by tree decays into (real) charm states
  
  \( \Gamma_{q_{12}} \) dominated by tree decays into (real) charm states
  
  \( \Gamma_{12} \) dominated by tree decays into (real) charm states

Model-independent parametrisation assuming NP affects \( M_{12} \) only

\[
M_{12}^q = (M_{12})_{SM} \times \Delta_q \quad \Delta_q = |\Delta_q| e^{i \phi_{\Delta q}} = (1 + h_q e^{2i \sigma_q})
\]

Affects \( \Delta m_q (\leftrightarrow |\Delta_q|), a_{SL}^q (\leftrightarrow \Delta_q), \Delta \Gamma_q \) and \( \phi_{Bq} (\leftrightarrow \phi_{\Delta q}) \)

Can use \( \Delta m_d, \Delta m_s, \beta, \phi_s, a_{SL}^d, a_{SL}^s, \Delta \Gamma_s \) to constrain \( \Delta_d \) and \( \Delta_s \)
$\Delta F = 2$: $B_d$ mixing

$$\Delta_d = 0.94^{+0.18}_{-0.15} + i \cdot (-0.11^{+0.11}_{-0.05})$$

2D SM hyp. ($\Delta_d = 1 + i \cdot 0$): 0.9 $\sigma$

[Constraints @ 68% CL]
- Dominant constraint from $\beta$ and $\Delta m_d$
- Good agreement with other constraints ($\alpha$, $a_{SL}^{d,s}$)
- Compatible with SM
- Still room for NP in $\Delta_d$

Excluded area has CL > 0.68
\( \Delta F = 2: B_s \) mixing

[Constraints @ 68% CL]
- Dominant constraints from \( \Delta m_s \) and \( \phi_s \)
- \( \phi_s \) favours SM situation
- \( A_{SL} \), combining \( a_{SL}^d \) and \( a_{SL}^s \), measured by \( D\phi \) not included
- still room for NP in \( \Delta_s \)

\[
\Delta_s = 1.05^{+0.14}_{-0.13} + i \cdot (-0.03^{+0.04}_{-0.04})
\]

2D SM hyp (\( \Delta_s = 1 + i \cdot 0 \)): 0.3 \( \sigma \)

Bounds/prospects for New Physics in future
- **Stage I**: 7 fb\(^{-1} \) LHCb data + 5 ab\(^{-1} \) Belle II
- **Stage II**: 50 fb\(^{-1} \) LHCb data + 50 ab\(^{-1} \) Belle II

S. Descotes-Genon (LPT-Orsay)
\[ \Delta F = 2: \text{Inputs for prospective} \]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>2003</th>
<th>2013</th>
<th>Stage I</th>
<th>Stage II</th>
</tr>
</thead>
<tbody>
<tr>
<td>(</td>
<td>V_{ud}</td>
<td>)</td>
<td>0.9738 ± 0.0004</td>
<td>0.97425 ± 0 ± 0.00022</td>
</tr>
<tr>
<td>(</td>
<td>V_{us}</td>
<td>(K_{\ell 3}))</td>
<td>0.2228 ± 0.0039 ± 0.0018</td>
<td>0.2258 ± 0.0008 ± 0.0010</td>
</tr>
<tr>
<td>(</td>
<td>\epsilon_K</td>
<td>)</td>
<td>(2.282 ± 0.017) \times 10^{-3}</td>
<td>(2.282 ± 0.011) \times 10^{-3}</td>
</tr>
<tr>
<td>(\Delta m_d \ [ps^{-1}])</td>
<td>0.502 ± 0.006</td>
<td>0.507 ± 0.004</td>
<td>id</td>
<td>id</td>
</tr>
<tr>
<td>(\Delta m_s \ [ps^{-1}])</td>
<td>&gt; 14.5 [95% CL]</td>
<td>17.768 ± 0.024</td>
<td>id</td>
<td>id</td>
</tr>
<tr>
<td>(</td>
<td>V_{cb}</td>
<td>\times 10^3)</td>
<td>41.6 ± 0.58 ± 0.8</td>
<td>41.15 ± 0.33 ± 0.59</td>
</tr>
<tr>
<td>(</td>
<td>V_{ub}</td>
<td>\times 10^3)</td>
<td>3.90 ± 0.08 ± 0.68</td>
<td>3.75 ± 0.14 ± 0.26</td>
</tr>
<tr>
<td>(\sin 2\beta)</td>
<td>0.726 ± 0.037</td>
<td>0.679 ± 0.020</td>
<td>0.679 ± 0.016</td>
<td>0.679 ± 0.008</td>
</tr>
<tr>
<td>(\alpha \ (mod \pi))</td>
<td>—</td>
<td>(85.4^{+4.0}_{-3.8})^\circ</td>
<td>(91.5 ± 2)^\circ</td>
<td>(91.5 ± 1)^\circ</td>
</tr>
<tr>
<td>(\gamma \ (mod \pi))</td>
<td>—</td>
<td>(68.0^{+8.0}_{-8.5})^\circ</td>
<td>(67.1 ± 4)^\circ</td>
<td>(67.1 ± 1)^\circ</td>
</tr>
<tr>
<td>(\beta_s)</td>
<td>—</td>
<td>−0.005 ± 0.035</td>
<td>0.0178 ± 0.012</td>
<td>0.0178 ± 0.004</td>
</tr>
<tr>
<td>(B(B \to \tau \nu) \times 10^4)</td>
<td>—</td>
<td>1.15 ± 0.23</td>
<td>0.83 ± 0.10</td>
<td>0.83 ± 0.05</td>
</tr>
<tr>
<td>(B(B \to \mu \nu) \times 10^7)</td>
<td>—</td>
<td>—</td>
<td>3.7 ± 0.9</td>
<td>3.7 ± 0.2</td>
</tr>
<tr>
<td>(A_{SL}^d \times 10^4)</td>
<td>10 ± 140</td>
<td>23 ± 26</td>
<td>−7 ± 15</td>
<td>−7 ± 10</td>
</tr>
<tr>
<td>(A_{SL}^s \times 10^4)</td>
<td>—</td>
<td>−22 ± 52</td>
<td>0.3 ± 6.0</td>
<td>0.3 ± 2.0</td>
</tr>
<tr>
<td>(m_c)</td>
<td>1.2 ± 0 ± 0.2</td>
<td>1.286 ± 0.013 ± 0.040</td>
<td>1.286 ± 0.020</td>
<td>1.286 ± 0.010</td>
</tr>
<tr>
<td>(m_t)</td>
<td>167.0 ± 5.0</td>
<td>165.8 ± 0.54 ± 0.72</td>
<td>id</td>
<td>id</td>
</tr>
<tr>
<td>(\alpha_s(m_Z))</td>
<td>0.1172 ± 0 ± 0.0020</td>
<td>0.1184 ± 0 ± 0.0007</td>
<td>id</td>
<td>id</td>
</tr>
<tr>
<td>(B_K)</td>
<td>0.86 ± 0.06 ± 0.14</td>
<td>0.7615 ± 0.0026 ± 0.0137</td>
<td>0.774 ± 0.007</td>
<td>0.774 ± 0.004</td>
</tr>
<tr>
<td>(f_B) [GeV]</td>
<td>0.217 ± 0.012 ± 0.011</td>
<td>0.2256 ± 0.0012 ± 0.0054</td>
<td>0.232 ± 0.002</td>
<td>0.232 ± 0.001</td>
</tr>
<tr>
<td>(B_{Bs}/B_{Bd})</td>
<td>1.37 ± 0.14</td>
<td>1.326 ± 0.016 ± 0.040</td>
<td>1.214 ± 0.060</td>
<td>1.214 ± 0.010</td>
</tr>
<tr>
<td>(f_{Bs}/f_{Bd})</td>
<td>1.21 ± 0.05 ± 0.01</td>
<td>1.198 ± 0.008 ± 0.025</td>
<td>1.205 ± 0.010</td>
<td>1.205 ± 0.005</td>
</tr>
<tr>
<td>(B_{Bs}/B_{Bd})</td>
<td>1.00 ± 0.02</td>
<td>1.036 ± 0.013 ± 0.023</td>
<td>1.055 ± 0.010</td>
<td>1.055 ± 0.005</td>
</tr>
<tr>
<td>(\bar{B}<em>{Bs}/\bar{B}</em>{Bd})</td>
<td>—</td>
<td>1.01 ± 0 ± 0.03</td>
<td>1.03 ± 0.02</td>
<td>id</td>
</tr>
<tr>
<td>(\bar{B}_{Bs})</td>
<td>—</td>
<td>0.91 ± 0.03 ± 0.12</td>
<td>0.87 ± 0.06</td>
<td>id</td>
</tr>
</tbody>
</table>

Lattice QCD at the Intensity Frontier, Implications of LHCb measurements and future prospects, Physics at Super B Factory
\( \Delta F = 2 \): bounds on energy scale

### Stage I

From \( C_{ij}^2 / \Lambda^2 \times (\bar{b}_L \gamma^\mu q_{j,L})^2 \)

\[ h \simeq 1.5 \frac{|C_{ij}|^2}{|V_{ti}V_{tj}|^2} \frac{(4\pi)^2}{G_F \Lambda^2} \]

### Stage II

<table>
<thead>
<tr>
<th>Couplings</th>
<th>NP loop order</th>
<th>Scales (in TeV) probed by ( B_d ) mixing</th>
<th>( B_s ) mixing</th>
</tr>
</thead>
<tbody>
<tr>
<td>(</td>
<td>C_{ij}</td>
<td>=</td>
<td>V_{ti}V_{tj}^*</td>
</tr>
<tr>
<td>(</td>
<td>C_{ij}</td>
<td>= 1 ) (no hierarchy)</td>
<td>one loop</td>
</tr>
<tr>
<td></td>
<td>tree level</td>
<td>( 2 \times 10^3 )</td>
<td>( 5 \times 10^2 )</td>
</tr>
<tr>
<td></td>
<td>one loop</td>
<td>( 2 \times 10^2 )</td>
<td>40</td>
</tr>
</tbody>
</table>
Outlook

Flavour physics

- Connection between Higgs and fermion sectors
- Potential to unravel NP patterns in absence of direct production
- Analysis of flavour processes crucial

Determination of CKM matrix

- Mature field, with lattice accuracy often competing with exp
- No significant deviations in the global fit
- Other processes to include?
- $|V_{ub}|$ and $|V_{cb}|$?

Study of FCNC and NP

- $\Delta F = 1$: $B_s \rightarrow \mu \mu$, $K \rightarrow \pi \nu \bar{\nu}$
- $\Delta F = 2$: bounds for NP in mixing
- Prospectives for new processes studied/better inputs from lattice?
More information


J. Charles, Theory
O. Deschamps, LHCb
SDG, Theory
H. Lacker, ATLAS/BaBar
A. Menzel, ATLAS
S. Monteil, LHCb
V. Niess, LHCb
J. Ocariz, ATLAS/BaBar
J. Orloff, Theory
A. Perez, Babar
W. Qian, LHCb
V. Tisserand, BaBar/LHCb
K. Trabelsi, Belle/LHCb
P. Urquijo, Belle/Belle II
L. Vale Silva, Theory