What We've Learned from Experiments

Tim Gershon
University of Warwick & CERN

CKM2012, University of Cincinnati
29\textsuperscript{th} September 2012
The most permanent lessons in morals are those which come, not of booky teaching, but of experience.

Mark Twain, A Tramp Abroad
What We've Learned from Experiments since CKM2010

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First key to success: excellent accelerator performance

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First key to success: excellent accelerator performance

~ 433/fb $e^+e^-$ @ Y(4S)

~ 711/fb $e^+e^-$ @ Y(4S)

~ 12/fb 1.96 TeV $p\bar{p}$ collisions per experiment

ATLAS & CMS ~ 6/fb 7 TeV + 15/fb 8 TeV

LHCb ~ 1.2/fb 7 TeV + 1.5/fb 8 TeV $pp$ collisions
Novel detectors & analysis techniques
(just some examples from many)

BaBar DIRC detector for K/π ID

Neutral network based event reconstruction in Belle

LHCb VErtex LOcator

Heavy flavour triggers at hadron colliders
What do we know about CP violation?
Observed (5σ) CP violation effects

As listed in PDG 2012

- **Kaon sector**
  - $|\epsilon| = (2.228 \pm 0.011) \times 10^{-3}$
  - $\text{Re}(\epsilon'/\epsilon) = (1.65 \pm 0.26) \times 10^{-3}$

- **B sector**
  - $S_{\psi K_0} = +0.679 \pm 0.020$
  - $S_{\eta' K_0} = +0.59 \pm 0.07$, $S_{\phi K_0} = +0.74^{+0.11}_{-0.13}$, $S_{f_0 K_0} = +0.69^{+0.10}_{-0.12}$, $S_{K^+ K^- K_0} = +0.68^{+0.09}_{-0.10}$
  - $S_{\pi^+ \pi^-} = -0.65 \pm 0.07$, $C_{\pi^+ \pi^-} = -0.36 \pm 0.06$
  - $S_{\pi^0 \pi^0} = -0.93 \pm 0.15$, $S_{D^+ D^-} = -0.98 \pm 0.17$, $S_{D^{*+} D^{*-}} = -0.77 \pm 0.10$
  - $A_{K^+ \pi^\pm} = -0.087 \pm 0.008$
  - $A_{D(\text{CP}) K^\pm} = +0.19 \pm 0.03$

Only one in charged B mesons! Nothing yet in baryons, charm, leptons, ...

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Large CP violation effects exist
\[ \sin(2\beta) \] from \( B^0 \rightarrow J/\psi K^0 \)

**BABAR**

**BELLE**

World average: \( \sin(2\beta) = 0.679 \pm 0.020 \)

New results from LHCb to be presented in WGIV
... and T is also violated, as expected

Generalisation of usual sin(2β) analysis allowing for separate CP, T and CPT violating terms

No significant sign of CPT violation in any test

e.g. $A_T(\bar{B}^0 \to B_\pm)$ between $(l^- \text{ tag, } J/\psi K_S, \Delta t>0)$ and $(l^+ \text{ tag, } J/\psi K_L, \Delta t<0)$

$\sim \frac{1}{2}(\Delta S_T^+ \sin(\Delta m_d \Delta t) + \Delta C_T^+ \cos(\Delta m_d \Delta t))$
Large direct CP violation effects also exist

Large CP violation effects with strong variation across the Dalitz plot
Detailed studies will be necessary to understand origin of these effects

New results from LHCb to be presented in WGV

PLB 712 (2012) 203
Is there CP violation in the charm system? (and if so, where does it come from?)

To reduce systematics and (perhaps) enhance CP violation effect, experiments measure

$$\Delta A_{CP} \equiv A_{CP}(K^- K^+) - A_{CP}(\pi^- \pi^+)$$

$$= [a_{CP}^{\text{dir}}(K^- K^+) - a_{CP}^{\text{dir}}(\pi^- \pi^+)] + \frac{\Delta(t)}{\tau} a_{CP}^{\text{ind}}.$$  

$\Delta A_{CP}$ related mainly to direct CP violation (contribution from indirect CPV suppressed by difference in mean decay time)

$$\Delta a_{CP}^{\text{dir}} = (-0.68 \pm 0.15 \%)$$

Naïvely expected to be much smaller in the Standard Model

Must prepare ourselves for % level measurements

... are we too naïve? Or can we discover NP by better understanding of QCD?

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Is there CP violation in B mixing?

Semileptonic asymmetries in both $B_d$ and $B_s$ systems negligibly small in the SM

Results of inclusive dimuon asymmetry analysis $3.9\sigma$ from SM

Systematics reduced by magnet polarity inversions, and from use of control samples, such as single muon sample

$$A_{sl}^b = (0.594 \pm 0.022) a_{sl}^d + (0.406 \pm 0.022) a_{sl}^s$$

Constraint in $a_{sl}^d$–$a_{sl}^s$ plane obtained from oscillated $B_d$ or $B_s$ enriched samples (cutting on impact parameter)
Is there CP violation in B mixing?

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Including results on $a_{sl}^d$ and $a_{sl}^s$ individually (from $D^{(*)+}\mu^-\nu X$ and $D_s^+\mu^-\nu X$ samples) puts combination at $2.9\sigma$ from SM
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Including B factory $a_{sl}^{d}$ and LHCb $a_{sl}^{s}$ results give average 2.4σ from the SM

Situation unclear – improved measurements needed

Must prepare ourselves for ‰ level measurements

New results from BaBar to be presented in WGIV
The Unitarity Triangle

Disclaimer (I): other fitter groups are available
Disclaimer (ii): other Unitarity Triangles are available
(but this one really does deserve to be called “The” Unitarity Triangle)

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Many ways to measure $\beta$ … and all agree within current uncertainties

$\beta \equiv \phi_1$

$\sin(2\beta^{\text{eff}}) \equiv \sin(2\phi_1^{\text{eff}})$

$\sin(2\beta^{\text{eff}}) \equiv \sin(2\phi_1^{\text{eff}})$

$\diamond \equiv \text{new since CKM2010}$
\[ \alpha \equiv \varphi_2 \]
\[ \equiv \pi - \beta - \gamma \equiv \pi - \varphi_1 - \varphi_3 \]

Constraints from \( \pi\pi, \rho\pi, \rho\rho \) (also \( a_1 \pi \)). Combination dominated by \( \rho\rho \) – strong influence of single measurement of \( B^+ \to \rho^+\rho^0 \)

How well do we really know \( \alpha \)?

New results from BaBar to be presented in WGIV
\[ \gamma \equiv \varphi_3 \]

Precision on \( \gamma \) from tree-level decays (B \to DK) has stubbornly refused to go below 10° despite great efforts.

Precise measurements of several key observables now exist ... are we on the verge of more precise knowledge of \( \gamma \)?

New results from BaBar & LHCb to be presented in WGV
Perennial question for CKM workshops: how to extract clean (but still NP sensitive) weak phase information from hadronic B decays?

$$A_{\text{CP}}(K^-\pi^+) - A_{\text{CP}}(K^-\pi^0) \neq 0$$ puzzle persists

LHCb PRL 108 (2012) 201601

LHCb-CONF-2012-007

Suggestion in arXiv:1205.4948 to combine information in $B \to \pi\pi$ with $B_s \to K^+K^-$ – blurs boundary between $\alpha$ and $\gamma$
$\beta_s$ from $B_s \to J/\psi\phi$ & $J/\psi\pi\pi$

Significant improvements in precision ($\Delta \Gamma_s > 0$ now established)
Earlier hints of large anomalous effects not confirmed

n.b. $\sigma(\beta_s) \sim 4\sigma(\beta)$
The sides of the UT

Continued progress on measurements sensitive to $|V_{ub}|$, $|V_{cb}|$, $|V_{td}|$ & $|V_{ts}|$

**Belle LLWI preliminary**

$B^+ \rightarrow \pi^0 \ell \nu$

**BaBar arXiv:1208.1253**

$\omega \ell \nu$

$\eta \ell \nu$

$\eta' \ell \nu$

$B^0 \rightarrow \pi^+ \ell \nu$

$LHCb-CONF-2012-006$

$B^+ \rightarrow \rho^0 \ell \nu$

$B^0 \rightarrow \rho^+ \ell \nu$

Updated LHCb results to be shown in WG3

Can we measure $|V_{td}|$ & $|V_{ts}|$ from semileptonic decays?

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\[ |V_{ub}| \] from \{in,ex\}clusive semileptonic decays

PBFLB based on
BaBar PRD 83 (2011) 052011 &
PRD 83 (2011) 032007
Belle PRD 83 (2011) 071101(R)

Some tension between exclusive and inclusive results. PBFLB concludes:

\[ |V_{ub}|_{\text{excl}} = [3.23 (1 \pm 0.05_{\text{exp}} \pm 0.08_{\text{th}})] \times 10^{-3} \]
\[ |V_{ub}|_{\text{incl}} = [4.42 (1 \pm 0.045_{\text{exp}} \pm 0.034_{\text{th}})] \times 10^{-3}. \]

This average has a probability of \( P(\chi^2) = 0.003 \). Thus we scale the error by \( \sqrt{\chi^2} = 3.0 \) and arrive at

\[ |V_{ub}| = [3.95 (1 \pm 0.096_{\text{exp}} \pm 0.099_{\text{th}})] \times 10^{-3}. \]

Similar tension also for \( |V_{cb}| \)

Better understanding needed to reduce uncertainty
$B \to \tau \nu$ & $B \to D(*)\tau \nu$

BaBar arXiv:1207.0698
Belle arXiv:1208.4678
M. Nakao @ ICHEP

BaBar $[468M]$ (2010) semilep-tag
BaBar $[468M]$ (2012) hadronic-tag
BaBar (combined) with correlations
Belle $[657M]$ (2010) semilep-tag
Belle $[772M]$ (2012) hadronic-tag
Belle (combined) with correlations
W.A.
private average (MN)

$\sigma_{\text{SM}} (1.20 \pm 0.25) \times 10^{-4}$
$\sigma_{\text{CKM Fitter}} (0.73^{+0.12}_{-0.07}) \times 10^{-4}$

(1.70±0.80±0.20)×10⁻⁴
PRD81, 051101
(1.83 ± 0.53 ± 0.24)×10⁻⁴
arxiv:1207.0698
(1.79±0.48)×10⁻⁴
arxiv:1207.0698
(1.54 ± 0.38 ± 0.29)×10⁻⁴
PRD82, 071101
(0.72 ± 0.27 ± 0.11)×10⁻⁴
ICHEP 2012
(0.96±0.26)×10⁻⁴
ICHEP 2012
(1.15±0.23)×10⁻⁴
ICHEP 2012

Significance (from 0) below the usual threshold to claim observation

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BaBar PRL 109 (2012) 101802
Belle PRD82 (2010) 072005

BaBar rates 3.4σ above the SM, and inconsistent with 2HDM.
What do we know about rare decays?
Two routes to heaven for heavy quark flavour physics

CP violation (extra sources must exist)

But
- No guarantee of the scale
- No guarantee of effects in the quark sector
- Realistic prospects for CPV measurement in $\nu$ due to large $\theta_{13}$

SM

Rare decays (strong theoretical arguments)

But
- How high is the NP scale?
- Why have FCNC effects not been seen?

NP
b → sγ

The archetypal FCNC decay
New results on both inclusive properties and exclusive modes
$B^0 \to K^{*0} \mu^+ \mu^-$

LHCb-CONF-2012-008
BaBar Lake Louise
preliminary, also
CDF ICHEP preliminary
First measurement of the zero-crossing point of the forward-backward asymmetry

\[ q^2_0 = (4.9^{+1.1}_{-1.3}) \text{ GeV}^2 \]

(SM predictions in the range 4.0 – 4.3 GeV²)

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\[ B_s^0 \rightarrow \mu^+ \mu^- \]

ATLAS (2.4/fb) PLB 713 (2012) 387

CMS (5/fb) JHEP 04 (2012) 033

ATLAS $B(B_s \rightarrow \mu^+ \mu^-) < 2.2 \times 10^{-8}$ @ 95\% (90\%) CL

CMS $B(B_s \rightarrow \mu^+ \mu^-) < 7.7 \times 10^{-9}$ @ 95\% (90\%) CL

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\[ B_s^0 \rightarrow \mu^+\mu^- \]

Standard Model expectation, e.g. \((3.2 \pm 0.3) \times 10^{-9}\) 


N.B. Should be corrected up by 9% since time-integrated branching fraction is measured (arXiv:1204.1737)

<table>
<thead>
<tr>
<th>Mode</th>
<th>Limit</th>
<th>at 90% CL</th>
<th>at 95% CL</th>
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<tbody>
<tr>
<td>( B_s^0 \rightarrow \mu^+\mu^- )</td>
<td>Exp. bkg+SM</td>
<td>(6.3 \times 10^{-9})</td>
<td>(7.2 \times 10^{-9})</td>
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<td></td>
<td>Exp. bkg</td>
<td>(2.8 \times 10^{-9})</td>
<td>(3.4 \times 10^{-9})</td>
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<tr>
<td></td>
<td>Observed</td>
<td>(3.8 \times 10^{-9})</td>
<td>(4.5 \times 10^{-9})</td>
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<tr>
<td>( B^0 \rightarrow \mu^+\mu^- )</td>
<td>Exp. bkg</td>
<td>(0.91 \times 10^{-9})</td>
<td>(1.1 \times 10^{-9})</td>
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<tr>
<td></td>
<td>Observed</td>
<td>(0.81 \times 10^{-9})</td>
<td>(1.0 \times 10^{-9})</td>
</tr>
</tbody>
</table>

LHCb (1/fb) PRL 108 (2012) 231801

LHCb (1/fb) PRL 108 (2012) 231801

Updates hotly anticipated
Don't forget the bread and butter

- Most hadron collider heavy flavour results are ratios
  - e.g.
    \[
    B(B_s^0 \to \mu^+\mu^-) = B(B^+ \to J/\psi K^+) \times B(J/\psi \to \mu^+\mu^-) \times \frac{f_s}{f_d} \times \\
    \{ \frac{N(B_s^0 \to \mu^+\mu^-)}{\epsilon(B_s^0 \to \mu^+\mu^-)} / \frac{N(B^+ \to J/\psi K^+)}{\epsilon(B^+ \to J/\psi K^+)} \} 
    \]
  - where
    \[
    \frac{f_s}{f_d} = \{ \frac{N(B_s^0 \to D_s^- \mu^+X)}{\epsilon(B_s^0 \to D_s^- \mu^+X)} / \frac{N(B^0 \to D^- \mu^+X)}{\epsilon(B^0 \to D^- \mu^+X)} \} \times \\
    \frac{\tau(B^0)}{\tau(B_s^0)} \times \frac{B(D^- \to K^+\pi^-\pi^-)}{B(D_s^- \to K^+K^-\pi^-)} 
    \]
    (simplified expressions given here; other methods to determine $f_s/f_d$ also rely on $B(D_s^- \to K^+K^-\pi^-)$)
  - Limiting factor will become uncertainty on $B(D_s^- \to K^+K^-\pi^-)$
  - Improved measurements of basic quantities can have significant impact
Some morals

• Worship the accelerator gods
• Investment in detectors & techniques brings rewards
• Interesting effects might be very big …
  … or very small → be prepared to be precise
  … but it seems like there are no O(1) deviations from the SM
• Clean theoretical predictions are to be treasured …
  … data-driven methods to control uncertainties also to be valued
• $3\sigma$ often goes away, but $5\sigma$ seems to stay
  … but investigating anomalies is worth the effort
  – sure to learn something (about physics, systematics or statistics)
• Bread and butter can be needed before a feast
• New physics just might be around the corner …
  … plenty to look forward to in CKM2012 … and beyond