B-Flavour Physics in LHCb

Marcel Merk
On behalf of the LHCb collaboration
54th International Winter Meeting on Nuclear Physics
Bormio, Jan 25-29, 2016
Outline

1. Flavour Physics

2. The LHCb Experiment

3. CP Violation Measurements
   a) CP Violation in B-mixing: $a_{sl}^d$ and $a_{sl}^s$
   b) Direct CP Violation: CKM angle $\gamma$
   c) Time dependent CP violation: CKM angles $\phi_d$ and $\phi_s$

4. B Decay Rates
   a) Very Rare Decays: $B \rightarrow \mu\mu$
   b) Rare Decays: $b \rightarrow s$ quark transition
   c) Lepton Flavour Universality tests

5. Outlook
1. Flavour Physics

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Flavour Physics: perhaps a bit difficult...?
\[ L_{EW} = i \bar{\psi}_L \gamma_\mu D^\mu \psi_L + V(\phi) + Y_{ij} \left( \bar{\psi}_L^i \phi \right) \psi_R^j \]

- **Electroweak transition**: Electromagnetic and weak nuclear forces first differentiate
- **Supersymmetry breaking**: Axions etc.?
- **Grand unification transition**: Electroweak and strong nuclear forces differentiate
- **Quantum gravity wall**: Spacetime description breaks down

**Timeline**:
- **Today**: Life on earth (14 billion years)
- **Acceleration**: Dark energy dominates (11 billion years)
- **Solar system forms**: Star formation peak (8 billion years)
- **Galaxy formation era**: Earliest visible galaxies (700 million years)
- **Recombination**: Atoms form (400,000 years)
- **Matter domination**: Onset of gravitational collapse
- **Nucleosynthesis**: Light elements created – D, He, Li (10^2 min)
- **Nuclear fusion begins**: 1 μsec
- **Quark–hadron transition**: Protons and neutrons formed

**Quark Masses**:
- **Up Quark**: ~ 0.002 GeV
- **Charm Quark**: 1.25 GeV
- **Top Quark**: 175 GeV
- **Down Quark**: ~ 0.005 GeV
- **Strange Quark**: ~ 0.095 GeV
- **Bottom Quark**: 4.2 GeV

**CKM Matrix**

- **\( \sin 2\beta \)**
- **\( |V_{ub}| \)**
- **\( \Delta m_{21} \) & \( \Delta m_{32} \)
Mass vs Weak Eigenstates

\[
\begin{pmatrix}
  d' \\
  s' \\
  b'
\end{pmatrix} =
\begin{pmatrix}
  V_{ud} & V_{us} & V_{ub} \\
  V_{cd} & V_{cs} & V_{cb} \\
  V_{td} & V_{ts} & V_{tb}
\end{pmatrix}
\begin{pmatrix}
  d \\
  s \\
  b
\end{pmatrix}
\]

- The Higgs interaction \( Y_{ij} (\overline{\psi}_L \phi) \psi_R \) and the \( W \) interaction \( g \overline{\psi}_L (\gamma^\mu W^\mu) \psi_L \) do not agree on the quark eigenstates.
  - Relation is the CKM matrix \( V_{\text{CKM}} \),
  - Leads to three mixing angles and one free imaginary CP phase in the CKM.
- Quark CP violation emerged together with mass.
The CKM Matrix $V_{\text{CKM}}$

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

Wolfenstein parametrization: $V_{\text{CKM}}$

$$
\begin{pmatrix}
1 - \frac{1}{2}\lambda^2 & \lambda & A\lambda^3 (\rho - i\eta) \\
-\lambda & 1 - \frac{1}{2}\lambda^2 & A\lambda^2 \\
A\lambda^3 (1 - \rho - i\eta) & -A\lambda^2 & 1
\end{pmatrix}
$$

From unitarity ($V_{\text{CKM}} V_{\text{CKM}}^\dagger = 1$) CKM has four free parameters:
- 3 real: $\lambda$ ($\approx 0.22$), $A$ ($\approx 1$), $\rho$
- 1 imaginary: $i\eta$

Particle $\rightarrow$ Antiparticle: $V_{ij} \rightarrow V_{ij}^*$

$\Rightarrow$ 1 CP Violating phase
The CKM Matrix $V_{\text{CKM}}$

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\begin{pmatrix}
V_{ud} & V_{us} & V_{ub} \\
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V_{td} & V_{ts} & V_{tb}
\end{pmatrix}
$$

Wolfensteิน parametrization: $V_{\text{CKM}}$

$$
\begin{pmatrix}
|V_{ud}| & |V_{us}| & |V_{ub}| e^{-i\gamma} \\
-|V_{cd}| & |V_{cs}| & |V_{cb}| \\
|V_{td}| e^{-i\beta} & -|V_{ts}| e^{i\beta} & |V_{tb}|
\end{pmatrix}
$$

Can flavour physics explain the matter - antimatter asymmetry? \(\Rightarrow\) Requires New Physics!
**Direct vs Indirect search**

The **absolute** energy frontier:

- **Direct observation:**
  - Produce particles on-shell and detect decay products
  - More intuitive(?), “really” produced
  - Limited by collision energy

The **virtual** energy frontier:

- **Indirect observation:**
  - Less intuitive(?), quantum level
  - Limited by precision, not by collision energy
  - CP observables sensitive to imaginary couplings

**Indirect observations in the past:**

- Kaon decay $K^0 \rightarrow \mu\mu$ hints at c-quark via GIM in 1970 (J/Ψ produced in 1974)
- 3rd quark family predicted 1972 to explain CP violation (b produced in 1977, t in 1994)
- Neutral current discovered in neutrino experiment in 1973 (Z-boson produced in 1983)
- $B\bar{B}$ mixing (1987) hints at large top mass, LEP predicts top mass (1990) (top in 1994)
Indirect evidence for top mass and charm quark

\[ K^0 \rightarrow \mu\mu \text{ pointed to the charm quark} \]

GIM, Phys.Rev.D2,1285,1970

Weak Interactions with Lepton-Hadron Symmetry*

S. L. Glashow, J. Iliopoulos, and L. Maiani†
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138
(Received 5 March 1970)

We propose a model of weak interactions in which the currents are constructed out of four basic quark fields and interact with a charged massive vector boson. We show, to all orders in perturbation theory, that the leading divergences do not violate any strong-interaction symmetry and the next to the leading divergences respect all observed weak-interaction selection rules. The model features a remarkable symmetry between leptons and quarks. The extension of our model to a complete Yang-Mills theory is discussed.

\[ K^0 \rightarrow \mu\mu \ldots \]

We wish to propose a simple model in which the divergences are properly ordered. Our model is founded in a quark model, but one involving four, not three, fundamental fermions; the weak interactions are medi-

\[ q \rightarrow q \]

... new quantum number \( C \) for charm.

\[ d \rightarrow \bar{d} \]

\[ s \rightarrow \bar{s} \]

\[ \mu \rightarrow \mu \]

B\(^0\) mixing pointed to the top quark mass


DESY 87-029

April 1987

**OBSERVATION OF B\(^0\)-\(\bar{B}\)\(^0\) MIXING**

*The ARGUS Collaboration*

In summary, the combined evidence of the investigation of \( B^0 \) meson pairs, lepton pairs and \( B^0 \) meson-lepton events on the T(4S) leads to the conclusion that \( B^0-\bar{B}\)\(^0\) mixing has been observed and is substantial.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>( r &gt; 0.09 ) 90% C.L</td>
<td>This experiment</td>
</tr>
<tr>
<td>( x &gt; 0.44 )</td>
<td>This experiment</td>
</tr>
<tr>
<td>( B^0 f_B \approx f_\mu &lt; 160 \text{ MeV} )</td>
<td>( B ) meson ( (\approx \pi \text{ pion}) ) decay constant</td>
</tr>
<tr>
<td>( m_b &lt; 5 \text{ GeV}/c^2 )</td>
<td>( b ) quark mass</td>
</tr>
<tr>
<td>( \tau_b &lt; 1.4 \times 10^{-12} )</td>
<td>( B ) meson lifetime</td>
</tr>
<tr>
<td>(</td>
<td>V_{td}</td>
</tr>
<tr>
<td>( \rho_{QCD} &lt; 0.86 )</td>
<td>QCD correction factor [17]</td>
</tr>
<tr>
<td>( m_t &gt; 50 \text{ GeV}/c^2 )</td>
<td>( t ) quark mass</td>
</tr>
</tbody>
</table>
Higgs mass and Electroweak precision measurements

\[ M_W = M_W^0 + a m_t^2 + b \ln \left( \frac{M_H}{M_W} \right) \]

\[ W \text{ propagator (Z similar):} \]

\[ \begin{array}{c}
  \text{\( e^+ \)} \\
  H \\
  \text{\( e^- \)} \\
\end{array} \]

**• LEP**

"Indirect"

**• LHC**

"Direct"

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**6.1. Event selection**

For the 8 TeV process and the background is dominated by the jet multiplicity, as does the signal topology. Without accom-

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**6.2. Analysis**

The direct measurements of \[ m_H = 114.4 \text{ GeV} \] derived from the direct search at LEP-II. The result of a fit to the data of the sum of a signal component fixed to the respective fitted background component are displayed in (b) and (d).

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**Figure 8.13.**

[Image of a diagram showing Higgs mass and Electroweak precision measurements]
Why work on Flavor Physics?

(Nima Arkani-Hamed likes it too)
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LHCb @ LHC
Design:
• LHCb event rate: ~30 MHz
• 1 in 160 is a b-b event
• $10^{12}$ b-b events per year

• Background Suppression
• Flavour tagging
• Decay time measurement

• Vertex and momenta reconstruction
• Particle identification ($\pi, K, \mu, e, \gamma$)
• Trigger
Vertex Topology

Vertex Locator
Momentum and Mass Reconstruction

Trigger Tracker

Magnet

Outer Tracker
Particle Identification: $\pi, K, \mu, \gamma, e$
The LHCb Detector
The LHCb Detector
The LHCb Detector
LHCb Performance: $B_d/s$ Mixing

Trigger, background suppression, decay time reconstruction, flavour tagging: it works!

**$B^0 - \overline{B^0}$ mixing**

$B^0 \rightarrow D^- \pi^+$

![Graph of $B^0 \rightarrow D^- \pi^+$ decay](image)

**$B^0_s - \overline{B^0_s}$ mixing**

$B^0_s \rightarrow D_s^- \pi^+$

![Graph of $B^0_s \rightarrow D_s^- \pi^+$ decay](image)
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3. **CP Violation Measurements**
   a) CP Violation in B-mixing: $a_{sd}$ and $a_{sl}$
   
   b) Direct CP Violation: CKM angle $\gamma$
   
   c) Time dependent CP violation: CKM angles $\phi_d$ and $\phi_s$

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A slide of History on CP Violation

- **Charge Parity Violation in particle physics:**
  a) **1964 (CCFT):** Discovered in neutral Kaon beam “*indirect* CP violation”
     - Also called: *CPV in mixing*
     - \[ \text{Prob}(K^0 \rightarrow \bar{K}^0) \neq \text{Prob} (\bar{K}^0 \rightarrow K^0) \]
     - \[ |\epsilon| = (2.228 \pm 0.011) \times 10^{-3} \text{ (PDG 2014)} \]
  b) **1999 (NA48 & KTeV):** Seen in Kaon decays “*direct* CP violation”
     - Also called: *CPV in decay*
     - Decay rates \[ \Gamma(K^0 \rightarrow \pi^+\pi^-) \neq \Gamma(\bar{K}^0 \rightarrow \pi^+\pi^-) \]
     - \[ \text{Re}(\epsilon'/\epsilon) = (1.65 \pm 0.26) \times 10^{-3} \text{ (PDG 2014)} \]
  c) **2001 (Belle & Babar):** Observed in B mesons decays “CP violation in *interference*”
     - Also called: *mixing induced CPV*
     - \[ \sin 2\beta = 0.682 \pm 0.019 \text{ (PDG 2014)} \]

\[ \Rightarrow \text{Nobel prize 1980} \]
Observing CP Violation in B decays

- CP Violation occurs in *interference of two quantum amplitudes* that have a different CP odd (as well as CP even) phase.
  - Use the phenomenon of $B$-$\bar{B}$ mixing:
  - Interference of direct decay and decay via mixing leads to CP violation.

**Standard Model:**
- $B^0$-$\bar{B}^0$ phase $\phi_d = \arg(V_{td}) = 2\beta$
- $B_s$-$\bar{B}_s$ phase $\phi_s = \arg(V_{ts}) = -2\beta_s$
Observing CP Violation in B decays

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V_{td}e^{-i\beta} & V_{ts}e^{i\beta_s} & V_{tb}
\end{pmatrix}
\]
Feynman: “Remember the double slit experiment”

LHCb is a completely analogous interference experiment using B-mesons.

The $B_s$ system

- Can oscillate into its antiparticle
- The weak eigenstates are no longer $B_s$ and $\overline{B_s}$
- Two eigenstates with different mass and width

$B_s \rightarrow J/\psi \phi$

Look for interference of SM with NP
Probing new CP-violation with B mesons

- Look for *interference* of CKM with BSM amplitudes:
  a) SM Prediction: No CP violation a la kaons ("indirect" or "mixing")
     - $K \leftrightarrow \bar{K} = \epsilon \neq 0$ but $B \leftrightarrow \bar{B} = 0$
  b) Precise measurement of angle $\gamma$ “with trees” vs $\gamma$ “with loops” ("direct")
     - Many decay modes with tree and loop diagrams are available
  c) SM Prediction: $B_s$ box diagram phase $\phi_s = -2\beta_s \approx 0$ ("mixing induced")
     - New Physics “in the box”?

\[
\begin{pmatrix}
V_{ud} & V_{us} & V_{ub}e^{-i\gamma} \\
V_{cd} & V_{cs} & V_{cb} \\
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**CP Violation in Mixing**

- **Interference of the dispersive and absorptive amplitudes**
  - Similar to measurement \( \epsilon \) in kaon physics

- **Hamiltonian:**
  \[
  i \frac{d}{dt} \left( \begin{array}{c} B_s^0 \\ \overline{B}_s^0 \end{array} \right) = \left( \begin{array}{cc} M_{11} - \frac{i}{2} \Gamma_{11} & M_{12} - \frac{i}{2} \Gamma_{12} \\ M_{12}^* - \frac{i}{2} \Gamma_{12}^* & M_{22} - \frac{i}{2} \Gamma_{22} \end{array} \right) \left( \begin{array}{c} B_s^0 \\ \overline{B}_s^0 \end{array} \right)
  \]

- **Eigenstates:**
  \[
  M_L, M_H \\
  \Gamma_L, \Gamma_H
  \]
  \[
  \Delta M = M_H - M_L \\
  \Delta \Gamma = \Gamma_H - \Gamma_L
  \]

  \[
  \phi_{12} = \text{arg} \left( - \frac{M_{12}}{\Gamma_{12}} \right)
  \]

- **Observable:**
  \[
  a_{sl} = \frac{\Gamma \left( \overline{B}(t) \to f \right) - \Gamma \left( B(t) \to \overline{f} \right)}{\Gamma \left( B(t) \to f \right) + \Gamma \left( B(t) \to \overline{f} \right)} = \frac{\Delta \Gamma}{\Delta M} \tan \phi_{12}
  \]

- **In the Standard Model** \( \phi_{12} \approx 0.2^\circ \) for \( B_s \)
- \( B_{d,s} \): measure with flavor specific decays: \( B_{d,s} \to D_{(s)}^+ \mu^- \nu \) and C.C.

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*Lenz, Nierste JHEP.06 (2007) 072*
\[ A_{B\overline{B}} = \frac{N(D_{(s)}^- \mu^+, t) - N(D_{(s)}^+ \mu^-, t)}{N(D_{(s)}^- \mu^+, t) + N(D_{(s)}^+ \mu^-, t)} = \frac{a_{sl}}{2} + \left( \frac{a_p}{2} + \frac{a_{sl}}{2} \right) \frac{\cos \Delta M t}{\cosh \frac{\Delta \Gamma}{2} t} \]

\( a_{sl}^d \) (B\(_d\)) : must measure time-dependent

\( a_{sl}^s \) (B\(_s\)) : washout of fast oscillation factor and production asymmetry

**beauty (B\(_d\))**

\[ \Delta m_d = 0.5 \text{ ps}^{-1} \]

**beauty (B\(_s\))**

\[ \Delta m_s = 17.7 \text{ ps}^{-1} \]
Semileptonic charge asymmetry with $B_s$: $a_{sl}^s$

$$B_s \rightarrow D_s^+ \mu^- \nu$$

$$\mathcal{A}_{\text{meas}} = \frac{\Gamma[D_s^- \mu^+] - \Gamma[D_s^+ \mu^-]}{\Gamma[D_s^- \mu^+] + \Gamma[D_s^+ \mu^-]} = \frac{a_{sl}}{2}$$

Correct for detection asymmetry:

$$\frac{\epsilon(D_s^- \mu^+)}{\epsilon(D_s^+ \mu^-)}$$

LHCb:

$$a_{sl}^s = (-0.06 \pm 0.50 \pm 0.36)\%$$

(Update coming soon; error reduces by factor 2)

Standard Model:

$$a_{sl}^s = (1.9 \pm 0.3) \times 10^{-5}$$

Lenz, Nierste JHEP.06 (2007) 072

PLB 728C (2014) 607

Muon momentum [GeV]

LHCb

Magnet up

Magnet down

Muon momentum [GeV]
Semileptonic charge asymmetry with $B_d$: $a_{sl}^d$

**Time dependent analysis:**
- Decay time reconstruction with missing neutrino
- Background modelling

**LHCb:**

$$a_{sl}^d = (-0.02 \pm 0.19 \pm 0.30)\%$$

**Standard Model:**

$$a_{sl}^d = (-4.1 \pm 0.6) \times 10^{-4}$$
Semileptonic charge asymmetry with $B_d$: $a_{s_l}^d$

![Graph showing events vs time](image)

**LHCb:**

$$a_{s_l}^d = (-0.02 \pm 0.19 \pm 0.30)\%$$

**Standard Model:**

$$a_{s_l}^d = (-4.1 \pm 0.6) \times 10^{-4}$$

**Time dependent analysis:**
- Decay time reconstruction with missing neutrino
- Background modelling

**Results**

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$a_{s_l}^s$</th>
<th>$a_{s_l}^d$</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHCb</td>
<td></td>
<td>$-0.02 \pm 0.19 \pm 0.30$</td>
</tr>
<tr>
<td>Standard Model</td>
<td>$-4.1 \pm 0.6 \times 10^{-4}$</td>
<td></td>
</tr>
</tbody>
</table>

**References**

- LHCb: PRL 114 (2015) 041601
- Lenz, Nierste JHEP.06 (2007) 072
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Direct CP Violation with $B_{(s)} \rightarrow K\pi$ (“charmless”)

- Interference of trees and penguins
  - New physics can contribute to penguin loop
- Sensitive to $V_{ub}$ phase: CKM angle $\gamma$
- Measure the *untagged* CP asymmetry for $B^0$ and $B_s$ decays:

$$A_{CP} = \frac{\left( N_{B \rightarrow f} - N_{\bar{B} \rightarrow f} \right)}{\left( N_{\bar{B} \rightarrow f} + N_{B \rightarrow f} \right)}, \quad B \rightarrow f = \left\{ \begin{array}{l} B^0 \rightarrow K^+\pi^- \\ B_s \rightarrow \pi^+K^- \end{array} \right. $$

$$A_{raw} = A_{CP} + A_{det} + \kappa \cdot A_{prod}$$

(The correction factor is $O(1\%)$, measured from data)

| Instrumental asymmetry | Mixing dilution times production asymmetry |
Direct CP Violation with $B_{(s)} \rightarrow K\pi$ ("charmless")

**$B^0 \rightarrow K\pi$**

$A_{CP} = -0.080 \pm 0.007 \pm 0.003$

Most precise measurement of CP violation in a hadronic Machine.

**$B_s \rightarrow \pi K$**

$A_{CP} = 0.27 \pm 0.04 \pm 0.01$

First observation of a CP asymmetry in $B_s$ decays
Interference of trees and trees
- Interfere decays $b \rightarrow c$ with $b \rightarrow u$ to final states common to $D^0$ and $\bar{D}^0$.

Sensitive to $V_{ub}$ phase: CKM angle $\gamma$:

$$\frac{A(B^+ \rightarrow D^0 K^-)}{A(B^+ \rightarrow D^0 K^-)} = r_B e^{i\delta_B} e^{-i\gamma}$$

**GLW method:**

$f_D$ is a CP eigenstate common to $D^0$ and $\bar{D}^0$: $f_D = K^+K^-$, $\pi^+\pi^-$,...

Interfere: $B \rightarrow D^0K$, $B \rightarrow \bar{D}^0K$
- Large event rate; small interference.

**Gronau, London, Wyler:**

Direct CP Violation with $B \rightarrow D K$ (“charmed”)

- **Interference of trees and trees**
  - Interfere decays $b \rightarrow c$ with $b \rightarrow u$ to final states common to $D^0$ and $D^0$
- **Sensitive to $V_{ub}$ phase: CKM angle $\gamma$**:
  \[
  \frac{A(B^- \rightarrow \bar{D}^0 K^-)}{A(B^- \rightarrow D^0 K^-)} = r_B e^{i \delta_B} e^{-i \gamma}
  \]
- **Many methods**

**ADS method:**

Use common flavour state $f_D = (K^+ \pi^-)$

Note: decay $D^0 \rightarrow K^+ \pi^-$ is double Cabibbo suppressed

- Lower event rate; large interference

**Atwood, Dunietz, Soni:**

Phys Rev Lett 78, 3257 (1997)

Phys Rev D 63, 036005 (2001)
Direct CP Violation with $\text{B} \rightarrow \text{DK}$ ("charmed")

Observe ADS mode $\text{B}^- \rightarrow \text{[π}^\pm \text{K}^\mp\text{]}_\text{D} \text{K}^-$ with 10 $\sigma$ significance

GLW:

$A_{\text{CP}^+} = 0.145 +\ 0.032 +\ 0.010$
$R_{\text{CP}^+} = 1.007 +\ 0.038 +\ 0.012$

ADS:

$A_{\text{ADS}} = -0.52 +\ 0.15 +\ 0.02$
$R_{\text{ADS}} = 0.0152 +\ 0.0020 +\ 0.0004$

→ CP violation is observed with 5.8 $\sigma$
More methods/modes available: GLW, ADS, GGSZ, GLS...:
- $B^+ \rightarrow D h^+ \text{ with } D \rightarrow h h$ ; GLW/ADS method (2011 data): Phys.Lett.B712(212)203
- $B^+ \rightarrow D h^+ \text{ with } D \rightarrow K \pi \pi \pi$ ; ADS method (2011 data): Phys.Lett.B723(2013)44
- $B^+ \rightarrow D K^+ \text{ with } D \rightarrow K_s^0 h h$ ; GGSZ method (2011+2012 data) : arXiv:1408.2748
- $B^+ \rightarrow D K^+ \text{ with } D \rightarrow K_s^0 K \pi$ ; GLS method (2011+2012 data) : Phys.Lett B 733 (2014) 36
- $B^0 \rightarrow D^0 K^{*0} \text{ with } D \rightarrow h h$ ; GLW/ADS (2011+2012 data) : arXiv:1407.8136

Most precise $\gamma$ determination:

$\gamma_{B \rightarrow Dh} = \left(72.9^{+9.2}_{-9.9}\right)^\circ$
1. Flavour Physics

2. The LHCb Experiment

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Time Dependent CP Violation: mixing phase

\[ B \xrightarrow{e^{i\phi_d}} B \]

\[ B \xrightarrow{e^{i\phi_s}} B_s \]

\[ \mathcal{A}_{CP}(t) = \frac{\Gamma_{\bar{B} \to f}(t) - \Gamma_{B \to f}(t)}{\Gamma_{\bar{B} \to f}(t) + \Gamma_{B \to f}(t)} = \frac{\mathcal{A}_{dir} \cos(\Delta M t) + \mathcal{A}_{mix} \sin(\Delta M t)}{\cosh(\frac{\Delta \Gamma}{2} t) - \mathcal{A}_{\Delta \Gamma} \sinh(\frac{\Delta \Gamma}{2} t)} \]

\[ (\mathcal{A}_{dir})^2 + (\mathcal{A}_{mix})^2 + (\mathcal{A}_{\Delta \Gamma})^2 = 1 \]

- Extraction of \( \mathcal{A}_{dir} \) and \( \mathcal{A}_{mix} \) require flavour tagging: knowing the flavour of the B-meson at production
- Measure \( \phi_d \) (SM: \( \mathcal{A}_{mix} = \sin 2\beta \)) and \( \phi_s \) (SM: \( \mathcal{A}_{mix} = -\sin 2\beta_s \))
$\phi_d : B$-factory golden mode: $B^0 \rightarrow J/\psi K_s$

B-factories:
- Coherent production, clean flavour tag
  
Belle: PRL 108 (2012) 171802

- Babar:
  \[ \sin 2\beta = 0.662 \pm 0.039 \pm 0.012 \]

- Belle:
  \[ \sin 2\beta = 0.670 \pm 0.029 \pm 0.013 \]

- LHCb:
  (Not so golden mode for LHCb: $K_s$ decays often outside Velo)
  \[ \sin 2\beta = 0.731 \pm 0.035 \pm 0.020 \]

(CKM Mixing Phase: $\phi_d = 2\beta$)
\( \phi_d : \) B-factory golden mode: \( B^0 \rightarrow J/\psi K_s \)

- **Babar:**
  \[
  \sin 2\beta = 0.662 \pm 0.039 \pm 0.012
  \]

- **Belle:**
  \[
  \sin 2\beta = 0.670 \pm 0.029 \pm 0.013
  \]

- **LHCb:**
  \[
  \sin 2\beta = 0.731 \pm 0.035 \pm 0.020
  \]
  (Not so golden mode for LHCb: \( K_s \) decays often outside Velo)

(CKM Mixing Phase: \( \phi_d = 2\beta \))
$\phi_s : \text{LHCb golden mode: } B_s \to J/\psi \phi$

Two decay amplitudes to the same CP eigenstate final state.

1) via mixing $B_s \to \overline{B}_s \to J/\psi \phi$:

2) direct: $B_s \to J/\psi \phi$:

- Golden mode for a time dependent measurement of "$\phi_s$ via mixing diagram"
  - Hadronic uncertainties small
- Sensitive to new physics that enters via the mixing loop
- $B_s$ is a pseudoscalar ($s=0$) while $J/\psi$ and $\phi$ are vector particles ($s=1$)
  - Final state is superposition of CP even ($L=0$ and $L=2$) CP odd ($L=1$)
  - Requires angular analysis to disentangle
- Alternative analysis in pure CP odd eigenstate $B_s \to J/\psi \pi^+\pi^-$

(CKM Mixing Phase: $\phi_s = -2\beta_s \approx 0$)
\( \phi_s : \text{LHCb golden mode: } B_s \rightarrow J/\psi \phi \)

- Requires combined decay time and angular analysis to statistically disentangle the CP even and CP odd amplitudes...
\[ \phi_s : \text{LHCb golden mode: } B_s \rightarrow J/\psi \phi \]

**LHCb:**
\[ \phi_s = -0.010 \pm 0.039 \text{ [rad]} \]

**Standard Model:**
\[ \phi_s = -2\beta_s = -0.0376 \pm 0.0008 \text{ [rad]} \]

Consistent.

2011 + 2012 data: 3 fb\(^{-1}\)
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5. Outlook
Effective Couplings

- **Beta decay**: “charged current”:

\[
\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2}
\]

- **Rare B decay**: “Flavour changing neutral current”:

\[
\sum_i C_i \mathcal{O}_i
\]

- Effective local Operators \( \mathcal{O}_i \) with Wilson coefficients \( C_i \) predicted by the Standard Model.
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5. Outlook
**Very Rare Decays**

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

**SM:** CKM and helicity suppressed: very small B.R.
→ Axial vector coupling \( C_{10} \)

\[
\text{BR} (B_s^0 \rightarrow \mu^+ \mu^-) = (3.66 \pm 0.23) \times 10^{-9}
\]
\[
\text{BR} (B_d^0 \rightarrow \mu^+ \mu^-) = (1.06 \pm 0.09) \times 10^{-10}
\]

**NP:** Sensitive to new particles via additional \( (C_{10}, C_S, C_P) \) couplings.
→ e.g.: \( Z' \), (pseudo-)scalars, ...

\[
\text{BR} \propto |V_{tb}V_{tq}|^2 \left[ (1 - \frac{4m_\mu^2}{M_B^2}) |C_S - C_S'|^2 + |(C_P - C'_P) + \frac{2m_\mu}{M_B^2}(C_{10} - C'_{10})|^2 \right]
\]
Very Rare Decays

LHCb experiment
Run: 101412  Event: 8681643
Date: 8 Sep 2011 Time: 16:04:18

Multivariate technique to suppress Backgrounds.
- Detached vertex
- Muon identification
Very Rare Decays

$B^0_{d/s} \rightarrow \mu^+\mu^-$

- LHCb + CMS combined signal:

$$BR\left(B_s^0 \rightarrow \mu^+\mu^-\right) = (2.8 \pm 0.7) \times 10^{-9}$$

$$BR\left(B_d^0 \rightarrow \mu^+\mu^-\right) = (3.9 \pm 1.5) \times 10^{-10}$$

Consistent with SM at ~ 2σ

Hot topic for LHC Run-2!

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2. The LHCb Experiment

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5. Outlook
b → s quark transition

• Effective 4-fermion coupling:

\[ \mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i C_i O_i \]

• Standard Model:
  – No flavour changing neutral currents: loops → suppressed amplitudes

  **Photon penguin:**

  \[ b \rightarrow W \rightarrow s \]

  \[ O_7 \]

  **Vector, Axial vector:**

  \[ b \rightarrow W \rightarrow s \]

  \[ O_9, O_{10} \]

• New Physics:
  – Sensitivity for NP in Wilson coefficients \( C_7, C_9, C_{10} \)
Rare Decays: $b \rightarrow s \mu^+ \mu^-$

$B_d^0 \rightarrow K^* \mu^+ \mu^-$

The decay $B_0 \rightarrow K^{*0} \mu^+ \mu^-$ is in the SM only possible at loop level. On the other hand, NP can show up at either tree or loop level.

Angular analysis of 4-body final state brings a large number of observables.

Interference between these and their right-handed counterparts.

EW penguins.
$B_d^0 \rightarrow K^* \mu^+ \mu^-$

- Study the angular distribution of the final state particles:

$$\tilde{\Omega} \equiv (\cos \theta_l, \cos \theta_K, \phi)$$

$$d^4 \Gamma [B^0 \rightarrow K^{*0} \mu^+ \mu^-] = \frac{9}{32 \pi} \sum_j I_j (q^2) f_j (\tilde{\Omega})$$

- Observables:

$$S_j = (I_j + \bar{I}_j) / \left( \frac{d \Gamma}{dq^2} + \frac{d \bar{\Gamma}}{dq^2} \right)$$

$$A_j = (I_j - \bar{I}_j) / \left( \frac{d \Gamma}{dq^2} + \frac{d \bar{\Gamma}}{dq^2} \right)$$

$LHCb$
Rare Decays: $b \rightarrow s \, \mu^+ \mu^-$

$B_d^0 \rightarrow K^* \mu^+ \mu^-$

Observables $S_5, P'_5$:

- $S_5$ variable: count blue minus red
- "Robust" $P'_5$ variable: $P'_5 = \frac{S_5}{\sqrt{F_L (1 - F_L)}}$

($F_L =$ longitudinal polarisation $K^*$)

$P'_5$ vs $q^2$ shows deviations from SM:

- $2.8 \sigma, 3.0 \sigma$ from SM

Determined from a maximum likelihood fit to the data. The shaded boxes show the SM prediction taken from Ref. [14].

Fit the value of Wilson coefficient:

$$C_9 = C_9^{SM} + C_9^{NP}$$

points at $C_9^{NP} \sim -1$

Warning: hadronic uncertainties (cc)

See talk Matthias Neubert:
Rare Decays: $b \to s \mu^+\mu^-$

- Branching fractions related to $b \to s \mu^+\mu^-$ transition consistently lower than predicted.
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Lepton Universality: $B^+ \to K^+ \mu^+\mu^- / B^+ \to K^+ e^+e^-$

- Standard Model: $b \to s l^+l^-$ is flavour universal.
- Expect equal branching fractions for $b \to s \mu^+\mu^-$ and $b \to s e^+e^-$
  - (Hadronic uncertainties largely cancel in the ratio)

$$R_K \equiv \frac{\mathcal{B}(B^+ \to K^+ \mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+ e^+e^-)} \overset{\text{SM}}{=} 1 \pm \mathcal{O}(10^{-2})$$

$(R_{K^*} \text{ coming soon})$
Lepton Universality: \( B^+ \rightarrow K^+ \mu^+\mu^- / B^+ \rightarrow K^+ e^+e^- \)

- Standard Model: \( b \rightarrow s \) is flavour universal.
- Expect equal branching fractions for \( b \rightarrow s \mu^+\mu^- \) and \( b \rightarrow s e^+e^- \)
  - (Hadronic uncertainties largely cancel in the ratio)

\[
R_K \equiv \frac{\mathcal{B}(B^+ \rightarrow K^+ \mu^+\mu^-)}{\mathcal{B}(B^+ \rightarrow K^+ e^+e^-)} = 1 \pm \mathcal{O}(10^{-2})
\]

\( R_{K^*} \) coming soon

\[
R_K = 0.745^{+0.090}_{-0.074} \pm 0.036
\]

\( R_K \neq 1 \) would imply NP with non-universal lepton couplings.
Lepton Universality: $B \rightarrow D^{*}\tau\nu / B \rightarrow D^{*}\mu\nu$

Before LHCb:

- Belle 2007
- BaBar 2008
- Belle 2009
- Belle 2010
- BaBar 2012

$R_{D^*} \equiv \frac{B(B \rightarrow D^{*}\tau\nu)}{B(B \rightarrow D^{*}\mu\nu)}$ (≠ 1 due to phase space!)

$\Delta \chi^2 = 1.0$

3.9 $\sigma$ from SM

$P(\chi^2) = 55\%$
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5. Outlook
The Future – LHCb Upgrade

VErtex LOcator
new (silicon pixels)

RICH detectors
new photon detectors (SiPM)
   improve RICH1 optics

Muon system
new off-detector electronics

interaction point

Tracking system
new (silicon strips, scintillating fibres)

Calorimeters
new readout electronics
Andreas Schopper
The future of triggers
5 August 2015
LISHEP 2015

Triggers today

Triggers in the future

Gligorov 2014
### Expected statistical uncertainties before and after upgrade

<table>
<thead>
<tr>
<th>Type</th>
<th>Observable</th>
<th>LHC Run 1</th>
<th>LHCb 2018</th>
<th>Upgrade 50/fb</th>
<th>Theory</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_s^0$ mixing</td>
<td>$\phi_s B_s^0 \to J/\psi \phi$ (rad)</td>
<td>0.049</td>
<td>0.025</td>
<td>0.009</td>
<td>$\sim 0.003$</td>
</tr>
<tr>
<td></td>
<td>$\phi_s B_s^0 \to J/\psi f_0(980)$ (rad)</td>
<td>0.068</td>
<td>0.035</td>
<td>0.012</td>
<td>$\sim 0.01$</td>
</tr>
<tr>
<td></td>
<td>$A_{sl}(B_s^0)$ ($10^{-3}$)</td>
<td>2.8</td>
<td>1.4</td>
<td>0.5</td>
<td>0.03</td>
</tr>
<tr>
<td>Gluonic penguin</td>
<td>$\phi_s^{\text{eff}} B_s^0 \to \phi \phi$ (rad)</td>
<td>0.15</td>
<td>0.10</td>
<td>0.018</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>$\phi_s^{\text{eff}} B_s^0 \to K^{*0} \bar{K}^{*0}$ (rad)</td>
<td>0.19</td>
<td>0.13</td>
<td>0.023</td>
<td>$&lt; 0.02$</td>
</tr>
<tr>
<td></td>
<td>$2\beta^{\text{eff}} B_s^0 \to \phi K^0_S$ (rad)</td>
<td>0.30</td>
<td>0.20</td>
<td>0.036</td>
<td>0.02</td>
</tr>
<tr>
<td>Right-handed currents</td>
<td>$\phi_s^{\text{eff}} B_s^0 \to \phi \gamma$ (rad)</td>
<td>0.20</td>
<td>0.13</td>
<td>0.025</td>
<td>$&lt; 0.01$</td>
</tr>
<tr>
<td></td>
<td>$\tau^{\text{eff}} B_s^0 \to \phi \gamma / \tau_{B_s^0}$</td>
<td>5%</td>
<td>3.2%</td>
<td>0.6%</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>0.04</td>
<td>0.020</td>
<td>0.007</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>$q_0 A_{FB}(B^0 \to K^{*0} \mu^+ \mu^-)$</td>
<td>10%</td>
<td>5%</td>
<td>1.9%</td>
<td>$\sim 7%$</td>
</tr>
<tr>
<td></td>
<td>$A_{\text{F}}(K \mu^+ \mu^- ; 1 &lt; q^2 &lt; 6 \text{GeV}^2/c^4)$</td>
<td>0.09</td>
<td>0.05</td>
<td>0.017</td>
<td>$&lt; 0.02$</td>
</tr>
<tr>
<td></td>
<td>$B(B^+ \to \pi^+ \mu^+ \mu^-)/B(B^0 \to K^+ \mu^+ \mu^-)$</td>
<td>14%</td>
<td>7%</td>
<td>2.4%</td>
<td>$\sim 10%$</td>
</tr>
<tr>
<td>Higgs penguin</td>
<td>$B(B_s^0 \to \mu^+ \mu^-)$ ($10^{-9}$)</td>
<td>1.0</td>
<td>0.5</td>
<td>0.19</td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td>$B(B^0 \to \mu^+ \mu^-)/B(B_s^0 \to \mu^+ \mu^-)$</td>
<td>220%</td>
<td>110%</td>
<td>40%</td>
<td>$\sim 5%$</td>
</tr>
<tr>
<td>Unitarity triangle</td>
<td>$\gamma(B \to D^{(<em>)} K^{(</em>)})$</td>
<td>7°</td>
<td>4°</td>
<td>0.9°</td>
<td>negligible</td>
</tr>
<tr>
<td></td>
<td>$\gamma(B_s^0 \to D_s^+ K^{(*)})$</td>
<td>17°</td>
<td>11°</td>
<td>2.0°</td>
<td>negligible</td>
</tr>
<tr>
<td></td>
<td>$\beta(B^0 \to J/\psi K^0_S)$</td>
<td>1.7°</td>
<td>0.8°</td>
<td>0.31°</td>
<td>negligible</td>
</tr>
<tr>
<td>Charm</td>
<td>$A_{\Gamma}(D^0 \to K^+ K^-)$ ($10^{-4}$)</td>
<td>3.4</td>
<td>2.2</td>
<td>0.4</td>
<td>–</td>
</tr>
<tr>
<td>CP violation</td>
<td>$\Delta A_{CP}$ ($10^{-3}$)</td>
<td>0.8</td>
<td>0.5</td>
<td>0.1</td>
<td>–</td>
</tr>
</tbody>
</table>

Comparable precision for experiment & theory after upgrade.
LHCb is more than b-physics...

General Purpose detector in the forward region:
- Charm physics
- Electroweak Physics: W, Z
- Exotica & Majorana particles searches
- Spectroscopy (see S. Neubert)
- QCD & Heavy Ion physics (Pb-Pb, p-Pb) (see M. Schmelling)
- Focus on b-physics remains

Welcome the competition!
Thank you for your attention!