The **LHCb** experiment: status and physics program

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FPCP Paris, 2-6 June 2003
**The LHCb experiment**

**LHCb is a forward one-arm spectrometer dedicated mainly to study CP violation and rare B decays at LHC**

Check consistency of the **Standard Model**: precision measurements of angles and sides of the CKM triangle

Search for **New Physics**: rare and SM forbidden decays of b particles
The triangle

Consistency of the Standard Model (assumed to determine the vertex) and the direct measurement of $\sin 2\beta$ from B-factories

$|V_{cb}|$ from $B \rightarrow H_c X$ decays $\rightarrow A$

$|V_{ub}|$ from $B \rightarrow H_u \ell \nu$ decays $\rightarrow \rho^2 + \eta^2$

$B_d$-$B_d$ mixing, $\Delta m_d \rightarrow (1-\rho)^2 + \eta^2$

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\[ \Delta b = 1 : \text{Decays through penguin} \]

\[ \Delta b = 2 : \text{Oscillations through box} \]

\[ \Delta b = 2 : \text{Oscillations through tree} \]

The Standard Model tree process not affected.
### b at the LHC machine

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{cm}$</td>
<td>14 TeV</td>
</tr>
<tr>
<td>$L (cm^{-2} s^{-1})$</td>
<td>$2 \times 10^{32}$ (10-100)</td>
</tr>
<tr>
<td>$\sigma (bb)$</td>
<td>500 $\mu$b</td>
</tr>
<tr>
<td>$\sigma (inel)$</td>
<td>80 mb</td>
</tr>
<tr>
<td>$#bb$-pairs</td>
<td>$10^{12}$ /year</td>
</tr>
<tr>
<td>$b$ fraction</td>
<td>$5 \times 10^{-3}$</td>
</tr>
<tr>
<td>$f$</td>
<td>40 MHz</td>
</tr>
<tr>
<td>$t_{bunch}$</td>
<td>25 ns</td>
</tr>
<tr>
<td>$z$ primary</td>
<td>5 cm</td>
</tr>
<tr>
<td>inter/xing</td>
<td>0.4 (2-20)</td>
</tr>
</tbody>
</table>

**Luminosity locally controlled**

All types of b-hadrons $B_u$, $B_d$, $B_s$, $B_c$, $\Lambda_b$, $\Sigma_b$, $\Xi_b$, ...

with large boost of the hadron

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Crucial **tasks** of a detector:

- **triggering**
- **particle ID** identification of exclusive final states (K/π/p/e/µ) **tagging**
- **background rejection**
- **decay time resolution**
The LHCb detector layout

**Aperture**

\[ 1.5 < |\eta| < 3.5 \]

**Aperture ~ 15 – 300 (250) mrad**

**Ecal**

- Shashlik type (66 layers 2mm Pb/4mm scintillator)
- Transverse granularity 4, 6, 12 cm cells
- ~6000 channels, 25 \( \lambda_0 \)
- \( \sigma/E \sim 10%/\sqrt{E} \)

**Hcal**

- 1468 cells, 5.6 \( \lambda_0 \)
- \( \sigma/E \sim 75%/\sqrt{E} \)

**Dipole magnet**

- Warm trapezoidal coils
- Pole shape following the acceptance
- \( \int B dl = 4 Tm \)
- \( P = 4.2 MW \)

**Inner Tracker**

- 3 stations 4 layers each
- 320 \( \mu m \) thin silicon
- 198 \( \mu m \) readout pitch
- 130k readout channels

**Outer Tracker**

- 3 stations with 4 double layers
- 5 mm straws tubes
- Fast drift gas (signal within 50 ns)
- 75% Ar 15% CF4 10% CO2
- 50k readout channels

**Vertex Detector**

- \( 40\% \ X_0 \), 12%
The LHCb Vertex Locator

- low occupancy
- Si area: 0.32 m²
- $#X_o: 0.18$
- $\sigma_t: 43$ fs
- # channels: 172 k

$$\sigma_{IP} = 17 \mu m + \frac{32 \mu m}{p_T}$$

21 stations
Tracking performance

Average efficiency = **92 %**
Efficiency for p>5GeV >95%
Ghost rate p_T>0.5 GeV ~ 7%.

Momentum resolution:
\[ \Delta p/p = 0.38\% \]
\[ <N> = 27 \text{ tracks/event} \]

Mass resolution
\((\sim 13 \text{ MeV})\)
for the decay channel
\[ B_s \rightarrow D_s \pi^+ \rightarrow K\bar{K}\pi \]

Proper time resolution (42 fs)
The **RICH** of **LHCb**

2 detectors with 3 radiators (aerogel, C$_4$F$_{10}$, CF$_4$) cover momentum range: 2 - 100 GeV

**K–π separation**

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Physics with Particle Identification

**$B_s \rightarrow D_s K$**

- **Purity = 7.0%**
- **Efficiency = 66%**

**$B_s \rightarrow K^+ K^-$**

- **Purity = 13%**
- **Efficiency = 84%**
LHCb Trigger

subdetectors

Calorimeters
Muon
Pile-up veto

Level-0

VELO
Trigger Tracker
Level-0

all the detector

Higher Levels

data log

Level-1

40 MHz
\( p_T \) of e, \( \mu \), h, \( \gamma \)

1 MHz
Impact parameter
Rough \( p \) estimate
( \(~20\%\) )

40 KHz
final state reconstruction

200 Hz
LHCb L1 trigger

Performance in B decays

- trigger robust and flexible
- hadron trigger fundamental for hadronic final states
- trigger efficiencies L0 x L1 20 % - 70%

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Simulated bb events

MC Pythia 6.2 tuned on CDF and UA5 data
Multiple pp interactions and spill-over effects included
Complete description of material from TDRs
Individual detector responses tuned on test beam results
Complete pattern recognition in reconstruction
Yield calculated taking into account:

- Geometrical acceptance, detection efficiency, material
- L0 and L1 trigger efficiencies (including pile-up veto)
- Reconstruction efficiencies (tracking, calorimeters, PID)
- Selection cuts efficiency to identify the final state

<table>
<thead>
<tr>
<th>Channel</th>
<th>Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0 \rightarrow \pi^+ \pi^-$</td>
<td>27 k</td>
</tr>
<tr>
<td>$B^0 \rightarrow K^+ \pi^-$</td>
<td>115 k</td>
</tr>
<tr>
<td>$B_s \rightarrow K^+ K^-$</td>
<td>35 k</td>
</tr>
<tr>
<td>$B_s \rightarrow D_s^- \pi^+$</td>
<td>72 k</td>
</tr>
<tr>
<td>$B_s \rightarrow D_s^- K^+$</td>
<td>8 k</td>
</tr>
<tr>
<td>$B_s \rightarrow J/\psi (\mu^- \mu^+) \phi$</td>
<td>109 k</td>
</tr>
<tr>
<td>$B_s \rightarrow J/\psi (e^- e^+) \phi$</td>
<td>19 k</td>
</tr>
<tr>
<td>$B^0 \rightarrow J/\psi (\mu^- \mu^+) K_S$</td>
<td>119 k</td>
</tr>
<tr>
<td>$B^0 \rightarrow K^{0*} \gamma$</td>
<td>20 k</td>
</tr>
</tbody>
</table>

More background simulated events are necessary to optimize selection criteria vs background rejection.
4 ways of determining $\gamma$

- Time dependent analysis of $B_s \rightarrow D^+_s K^-$ (tagged)
- Rate difference between $B^- \rightarrow D^0 K^-$ and $B^+ \rightarrow D^0 K^+$ (untagged)
  model independent
- Rate measurements in $K^0 \pi^\pm$ and $K^\pm \pi^\mp$ (Fleisher-Mannel) or rates in $K^0 \pi^\pm$ and asymmetry in $K^\pm \pi^\circ$ (Neubert-Rosner, Beneke et al).
- Measure time dependent asymmetries in $B^0 \rightarrow \pi^+ \pi^-$ and $B_s \rightarrow K^+ K^-$ symmetric $d \leftrightarrow s$
  dependence on hadronic assumptions in the different calculations.
Measuring $\gamma$ with $B_s \rightarrow D_s^{\pm}K^+$

- must be separated from $B_s \rightarrow D_s \pi^+$
  (~15 times larger Br)
- hadronic trigger, $K/\pi$ separation, proper time resolution are fundamental
- gets $\gamma - 2\delta\gamma$
  (needs $2\delta\gamma$ from $B_s \rightarrow J/\Psi\Phi$)
- In one year of data (2 fb$^{-1}$)
  8k $D_s K$ and 72k $D_s \pi$
- expected sensitivity:
  \[
  \sigma(\gamma) \sim 10^0 \text{ for } \Delta m_s = 20 \text{ ps}^{-1} \\
  \sigma(\gamma) \sim 12^0 \text{ for } \Delta m_s = 30 \text{ ps}^{-1}
  \]
  depending on amplitudes, strong phases, $\gamma, \Delta m_s, \Delta \Gamma/\Gamma$

$B_s \rightarrow D_s \pi^+$ measure $B_s$ oscillations $\Delta m_s$ up to ~ 60 ps$^{-1}$

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Study of $B^0_s \rightarrow J/\psi \phi$ ($\mu\mu K^+K^-$)

- CP asymmetries determine $-2\delta\gamma$ (very small in Standard Model but sensitive to New Physics). And also $\Delta m_s$ and $\Delta \Gamma_s$
- Must be separated from prompt $J/\Psi$ production (possible with $0.1 < B/S < 0.4$ at 90% CL)

![Graphs showing proper time significance for $B^0_s \rightarrow J/\psi(\mu\mu)\phi$ signal and prompt $J/\psi(\mu\mu)$ background]
Study of $B^0_s \rightarrow J/\psi \ \phi$ \quad (\mu\mu \ K^+K^-)

- Needs angular analysis to disentangle CP-odd and CP-even states

- In one year of data (2 fb$^{-1}$)
  
  $109k \ J/\Psi \ \Phi$ and $19k \ J/\Psi \ \Phi$

  (\mu\mu) \quad (ee)

  expected sensitivity:

  $\sigma(2\delta\gamma) \sim 2^0$ for $\Delta m_s = 20 \text{ ps}^{-1}$

  also $B^0_s \rightarrow \Phi\Phi$ \quad $B^0_s \rightarrow J/\Psi \ \eta$ \quad $B^0_s \rightarrow \eta_c \ \Phi$ \quad probe $\delta\gamma$

(under study in LHCb)
Measuring $\gamma$ with $B_{(s)} \rightarrow \pi \pi, K \pi, K K$

- Relies on hadronic trigger, excellent $K/\pi$ separation, mass resolution
- Select $B$ candidates with $p_T$, IP/$\sigma$, L, mass cuts
- Combinatorial bb bckgr. can be rejected ($S/B > 1$)

$\sigma(\gamma) \sim 3^0$ for $x_s = 20$

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Present estimate of LHCb Physics reach

These numbers are being updated, and more channels studied, in the re-optimization of the LHCb detector to be concluded in September 2003

<table>
<thead>
<tr>
<th>Channel</th>
<th>Yield</th>
<th>Precision</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta B_d \to J/\psi K_s$</td>
<td>119 k</td>
<td>$\sigma(\beta) \approx 0.6^\circ$</td>
</tr>
<tr>
<td>$\gamma B_s \to D_s K$</td>
<td>8 k</td>
<td>$\sigma(\gamma) \approx 10^\circ$</td>
</tr>
<tr>
<td>$\alpha B_d \to \pi^+\pi^-$</td>
<td>27 k</td>
<td>$\sigma(\alpha) \approx 5^\circ - 10^\circ$</td>
</tr>
<tr>
<td>$2\delta\gamma B_s \to J/\psi \phi$</td>
<td>128 k</td>
<td>$\sigma(2\delta\gamma) \approx 2^\circ$</td>
</tr>
<tr>
<td>$</td>
<td>V_{td}/V_{ts}</td>
<td>B_s \to D_s \pi$</td>
</tr>
<tr>
<td>rare decays $B_d \to K^*\gamma$</td>
<td>20 k</td>
<td></td>
</tr>
</tbody>
</table>

1 year data $\Rightarrow$ 2 fb$^{-1}$
Conclusions

The present of b-physics is already very rich

B-factories (BaBar, Belle, CLEO), Tevatron, + (LEP, SLC)

The future:
Next generations of dedicated experiments at hadron machines will have order of $10^{12}$ $b\bar{b}$ pairs per year with dedicated trigger and particle ID

LHCb is a unique opportunity to measure precisely angles and sides of the CP triangle and to understand the origin of CP violation in the SM and beyond

LHCb installation starts in 2005
data taking starts in 2007
Back-up slides
<table>
<thead>
<tr>
<th>channel</th>
<th>L0 (%)</th>
<th>L1(%)</th>
<th>Total (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(\mu)</td>
<td>e</td>
<td>h</td>
</tr>
<tr>
<td>(B^0_s \rightarrow J/\psi(\mu\mu)\ \phi)</td>
<td>90</td>
<td>5</td>
<td>30</td>
</tr>
<tr>
<td>(B^0_s \rightarrow J/\psi(ee)\ \phi)</td>
<td>7</td>
<td>36</td>
<td>24</td>
</tr>
<tr>
<td>(B^0_s \rightarrow D_s K)</td>
<td>8</td>
<td>5</td>
<td>37</td>
</tr>
<tr>
<td>(B^0_d \rightarrow K^* \gamma)</td>
<td>6</td>
<td>28</td>
<td>30</td>
</tr>
<tr>
<td>(B^0_d \rightarrow \pi^+ \pi^-)</td>
<td>7</td>
<td>9</td>
<td>55</td>
</tr>
</tbody>
</table>