LHCb: a dedicated CP violation experiment at the LHC

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   3.4 Determination of $\gamma$
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Many thanks to many LHCb colleagues from whom I “borrowed” slides!
1. Physics aims

LHCb aims to test consistency of Standard Model interpretation of CP violation from B meson decays and to search for new physics.

- LHCb is a 2nd generation experiment that will determine CP violations in a variety of decays of $B_d$ and $B_s$ mesons to test consistency of Unitarity Triangles.

- It follows impressive results from the B-factories that have already established CP violation in a number of decay modes and are already constraining the unitarity triangle to unprecedented accuracy.
1. CP violation in Standard Model

Kobayashi and Maskawa (1973) extended idea of quark mixing (Cabibbo, 1964) to three quark families and provided explanation for CP violation:

Weak current:

\[ J_\mu = (\bar{u}, \bar{c}, \bar{t}) L \gamma_\mu V_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix}_L \]

Mixing weak eigenstates \((d', s', b')\)

mass eigenstates \((d, s, b)\):

\[ \begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = V_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix} \]

Cabibbo-Kobayashi-Maskawa (CKM) unitary matrix:

\[
V_{CKM} = \begin{pmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{pmatrix} = \begin{pmatrix}
c_{12} & s_{12} & 0 \\
-s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{pmatrix} \begin{pmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & -s_{23} & c_{23}
\end{pmatrix} \begin{pmatrix}
1 & 0 & 0 \\
0 & 1 & 0 \\
0 & 0 & e^{-i\delta}
\end{pmatrix} \begin{pmatrix}
c_{13} & 0 & s_{13} \\
0 & 1 & 0 \\
-s_{13} & 0 & c_{13}
\end{pmatrix}
\]

where \(c_{ij} = \cos \theta_{ij}\), and \(s_{ij} = \sin \theta_{ij}\)
1. CKM matrix

\[
V_{\text{CKM}} = \begin{pmatrix}
    c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\
    -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\
    s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13}
\end{pmatrix}
\]

(Experimentally)

\[
\begin{pmatrix}
    0.9739 - 0.9751 & 0.221 - 0.227 & 0.0029 - 0.0045 \\
    0.221 - 0.227 & 0.9730 - 0.9744 & 0.039 - 0.044 \\
    0.0048 - 0.014 & 0.037 - 0.043 & 0.9990 - 0.9992
\end{pmatrix}
\]

CKM matrix in Wolfenstein parametrization \( \sim \mathcal{O}(\lambda^5) \):

\[
\lambda = s_{12} = 0.2265 \quad A = \frac{s_{23}}{s_{12}} = 0.801 \quad \rho = \frac{s_{13} \cos \delta}{s_{12}s_{23}} \quad \eta = \frac{s_{13} \sin \delta}{s_{12}s_{23}}
\]

\[
(\bar{\rho}, \bar{\eta}) \equiv (1 - \lambda^2/2)(\rho, \eta) = (0.204, 0.340) \quad \beta = \tan^{-1} \left[ \frac{\bar{\eta}}{1 - \rho} \right] \quad \gamma = \tan^{-1} \frac{\eta}{\rho} \quad \chi = \eta \lambda^2 \approx 0.02
\]

\[
V_{\text{CKM}} = \begin{pmatrix}
    1 - \frac{\lambda^2}{2} + \frac{\lambda^4}{4} & \lambda & A\lambda^3(\rho - i \eta) \\
    -\lambda + \frac{A^4 \lambda^4}{2} - A^2 \lambda^5(\rho + i \eta) & 1 - \frac{\lambda^2}{2} + \frac{\lambda^4(1 - 2 \lambda^2)}{4} & A\lambda^2 \\
    A\lambda^3(1 - \bar{\rho} - i \bar{\eta}) & A\lambda^2 + A\lambda^4(1/2 - \rho - i \eta) & 1 - A^2 \frac{\lambda^4}{2}
\end{pmatrix} + \mathcal{O}(\lambda^6)
\]

\[
\begin{pmatrix}
    |V_{ud}| & |V_{us}| & -|V_{ub}|e^{-i\gamma} \\
    |V_{cd}| & |V_{cs}| & |V_{cb}|
\end{pmatrix}
\]

\( \beta : \)  \( B_d - \bar{B}_d \) Mixing Phase

\( \gamma : \)  \( B_d - B_d \) Mixing Phase

\( \chi = \delta \gamma : \)  \( B_s - \bar{B}_s \) Mixing Phase

Standard Model:

\( \alpha = \pi - \beta - \gamma \)

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1. Unitarity triangles

- Unitarity of CKM matrix ($\hat{V}_{CKM}^+ \hat{V}_{CKM} = 1$): 12 unitarity conditions
  - 6 normalisation conditions: $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$, etc…
  - 6 orthogonality conditions: 6 unitary triangles

\[
\begin{align*}
\text{(db)} & \quad V_{ud} V_{ub}^* + V_{cd} V_{cb}^* + V_{td} V_{tb}^* = 0 \\
\text{(sb)} & \quad V_{us} V_{ub}^* + V_{cs} V_{cb}^* + V_{ts} V_{tb}^* = 0 \\
\text{(ds)} & \quad V_{ud} V_{us}^* + V_{cd} V_{cs}^* + V_{td} V_{ts}^* = 0 \\
\text{(ct)} & \quad V_{ud} V_{cd}^* + V_{us} V_{cs}^* + V_{ub} V_{cb}^* = 0 \\
\text{(ut)} & \quad V_{ud} V_{td}^* + V_{us} V_{ts}^* + V_{ub} V_{tb}^* = 0 \\
\text{(uc)} & \quad V_{cd} V_{td}^* + V_{cs} V_{ts}^* + V_{cb} V_{tb}^* = 0
\end{align*}
\]
1. Unitarity triangles

- Two main unitarity triangles:
  \[ V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0 \]  
  \( \text{db} \)
  \[ V_{tb}V_{ub}^* + V_{ts}V_{us}^* + V_{td}V_{ud}^* = 0 \]  
  \( \text{ut} \)

Main goal B physics: determine angles and sides of unitarity triangles to understand origin of CP violation in B sector.
1. B mixing

Time development of neutral meson state $|B^0\rangle$ and its antiparticle

$$a(t) |B^0\rangle + b(t) |\overline{B^0}\rangle$$

governed by

$$i \frac{\partial}{\partial t} \begin{pmatrix} a \\ b \end{pmatrix} = H \begin{pmatrix} a \\ b \end{pmatrix} = \begin{pmatrix} M_{11} - \frac{i}{2} \Gamma_{11} & M_{12} - \frac{i}{2} \Gamma_{12} \\ M_{12}^* - \frac{i}{2} \Gamma_{12}^* & M_{22} - \frac{i}{2} \Gamma_{22} \end{pmatrix} \begin{pmatrix} a \\ b \end{pmatrix}$$

M mass matrix

CPT invariance $M_{11} = M_{22} = M$

$\Gamma_{11} = \Gamma_{22} = \Gamma$

Eigenstates of $H$:

$$|B_1\rangle = p |B^0\rangle + q |\overline{B^0}\rangle \quad |p|^2 + |q|^2 = 1$$

$$|B_2\rangle = p |B^0\rangle - q |\overline{B^0}\rangle$$

$p$ and $q$ represent the amount of state mixing
1. B mixing

From eigenvector equation

\[(H - EI)
\begin{pmatrix}
\pm q \\
p
\end{pmatrix}
= 0 \Rightarrow
\]

From time evolution of states

\[
\begin{align*}
|B^0(t)\rangle &= f_+(t) |B^0\rangle + \frac{q}{p} f_-(t) |\bar{B}^0\rangle \\

|B^0(t)\rangle &= f_+(t) |\bar{B}^0\rangle + \frac{p}{q} f_-(t) |B^0\rangle \\

|B_{1,2}(t)\rangle &= |B_{1,2}\rangle e^{-i \left( M_{1,2} - \frac{i}{2} \Gamma_{1,2} \right) t}
\end{align*}
\]

and

\[
\begin{align*}
P\left( B^0 \to B^0 : t \right) &= \left| \langle B^0 | B^0(t) \rangle \right|^2 = \left| f_+(t) \right|^2 = P\left( B^0 \to \bar{B}^0 : t \right) \\

P\left( \bar{B}^0 \to B^0 : t \right) &= \left| \langle \bar{B}^0 | B^0(t) \rangle \right|^2 = \left| \frac{q}{p} f_-(t) \right|^2 \\

P\left( \bar{B}^0 \to \bar{B}^0 : t \right) &= \left| \langle \bar{B}^0 | \bar{B}^0(t) \rangle \right|^2 = \left| \frac{p}{q} f_-(t) \right|^2 \\

\left| f_\pm(t) \right|^2 &= \frac{1}{4} \left[ e^{-\Gamma_1 t} + e^{-\Gamma_2 t} \pm 2 e^{-\Gamma t} \cos(\Delta M t) \right]
\end{align*}
\]

\[
\Gamma = \frac{\left( \Gamma_1 + \Gamma_2 \right)}{2}
\]

\[
\Delta M = M_2 - M_1
\]

\[
\Delta \Gamma = \Gamma_2 - \Gamma_1
\]

Mass and decay widths of 2 eigenstates

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## 1. B mixing

### Oscillation parameter

\[ \chi = \frac{\Delta M}{\Gamma} \]

\[ P(B^0 \rightarrow B^0 : t) \quad \text{solid line} \]

\[ P(B^0 \rightarrow \bar{B}^0 : t) \quad \text{dotted line} \]

### Kaon

\[ \frac{\Gamma_1}{\Gamma_L} = \frac{51.7 \pm 0.4 \text{ ns}}{0.08927 \pm 0.00009 \text{ ns}} \approx 580 \]

\[ \Delta M = (3.483 \pm 0.009) \times 10^{-15} \text{ GeV} \]

### B_d

\[ \Gamma_1 \approx \Gamma_2, \quad x \approx 1 \]

\[ \frac{\Delta \Gamma_d}{\Gamma_d} \approx 0.5\% \]

\[ \Delta M_d = (3.22 \pm 0.05) \times 10^{-13} \text{ GeV} \]

\[ x_d = 0.755 \pm 0.015 \]

### B_s

\[ \Gamma_1 \approx \Gamma_2, \quad x \approx 25 \]

\[ \frac{\Delta \Gamma_s}{\Gamma_s} \approx 15\%, \quad \Delta M_s > 10^{-11} \text{ GeV} \]

\[ x_s > 21.3 \]
1. CP violation in B decays

- CP violation in B meson decay: \( \Gamma_f \neq \Gamma_f \)

\[
A_f = \langle f | H | B^0 \rangle \quad A_f = \overline{\langle f | H | B^0 \rangle}
\]

\[
\Gamma_f \equiv \Gamma(B^0(t) \rightarrow f) = |A_f|^2 \left[ |f_+|^2 + \left( \frac{q}{p} \frac{A_f}{A_f} \right)^2 |f_-|^2 + 2 \text{Re} \left\{ \frac{q}{p} \frac{A_f}{A_f} f_+ f_-^* \right\} \right] \quad f_\pm = f_\pm(t)
\]

\[
\overline{\Gamma_f} \equiv \Gamma(\bar{B}^0(t) \rightarrow f) = |A_f|^2 \left[ \left| \frac{A_f}{A_f} \right|^2 |f_+|^2 + \left( \frac{p}{q} \right)^2 |f_-|^2 + 2 \left( \frac{p}{q} \right)^2 \text{Re} \left\{ \left( \frac{q}{p} \frac{A_f}{A_f} \right)^* f_+ f_- \right\} \right]
\]

- CP violation in the mixing (indirect CP violation): only source of CP violation from mixing matrix

\[
\left| \frac{q}{p} \right| \neq 1 \Rightarrow M_{12}^* - \frac{i}{2} \Gamma_{12}^* \neq M_{12} - \frac{i}{2} \Gamma_{12}
\]

- CP violation in the decay (direct CP violation):

\[
\left| \frac{A_f}{A_f} \right| = \left| \sum_i A_i e^{i\phi_i} e^{i\delta_i} \right| \neq 1 \quad \phi_i = \text{weak phase}
\]

\[
\sum_i A_i e^{-i\phi_i} e^{i\delta_i} \]

\[
\delta_i = \text{strong phase}
\]
1. CP violation in B decays

- CP violation in the interference of mixing and decay:
  - if $B^0$ and $\bar{B}^0$ decay to the same final state

$$B^0(t) \xrightarrow{p} B^0 \xrightarrow{A_f} f \neq B^0(t) \xrightarrow{q} \bar{B}^0 \xrightarrow{\bar{A}_f} f$$

Even if $p = q$ and $A_f = \bar{A}_f$, CP violation can occur:

$\Gamma_f \neq \bar{\Gamma}_f$ by interference of mixing and decay.

If $\lambda = \frac{q}{p} \frac{A_f}{\bar{A}_f}$ then CP violation when: $|\lambda| = 1, \quad \text{Im}\{\lambda\} \neq 0$

Asymmetry:

$$A_{CP}(t) = \frac{\Gamma_f - \bar{\Gamma}_f}{\Gamma_f + \bar{\Gamma}_f} = A^{dir} \cos(\Delta M t) + A^{int} \sin(\Delta M t)$$

$$A^{dir} = \frac{(1 - |\lambda|^2)}{(1 + |\lambda|^2)} \quad A^{int} = -2 \text{Im}\{\lambda\}/(1 + |\lambda|^2)$$
1. B decays in Standard Model

Tree

Box

Penguin

QCD

Electroweak

$V_{ub}, V_{cb}$

$u,c$
1. Status unitarity triangle

Consistent picture emerges:

CKM-fitter Winter 05 conferences

\[ \sqrt{\rho^2 + \eta^2} = \left(1 - \frac{\lambda^2}{2}\right) \frac{1}{\lambda} \left| \frac{V_{ub}}{V_{cb}} \right| \]

\[ \sqrt{(1 - \rho)^2 + \eta^2} = \frac{1}{\lambda} \left| \frac{V_{td}}{V_{cb}} \right| \approx \frac{1}{\lambda} \left| \frac{V_{td}}{V_{ts}} \right| \]

\[ \beta = \tan^{-1} \left( \frac{\eta}{1 - \rho} \right) \]

\[ \varepsilon_K \propto \eta (1 - \rho) \]

\[ \lambda = 0.2265^{+0.0020}_{-0.0020} \]

\[ A = 0.801^{+0.029}_{-0.018} \]

\[ \rho = 0.204^{+0.036}_{-0.043} \]

\[ \eta = 0.34^{+0.025}_{-0.022} \]
2. LHCb Experiment

- **LHCb Detector**: forward single arm spectrometer at LHC

**Acceptance:**
- 10-300 mrad bending
- 10-250 mrad non-bending
2. LHC accelerator
2. LHC accelerator

Collisions: 7 TeV protons on 7 TeV protons
Bunch crossing every 25 nsec (freq. = 40 MHz)
LHCb Luminosity: \( \sim 2 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1} \)
Number of pp inelastic interactions per crossing \( (\sigma_{\text{inelastic}} = 80 \text{ mb}) \), 0, 1, 2…

Forward geometry to exploit \( b\bar{b} \)
forward-backward production
2. LHCb detector

- Tracking stations (inner and outer)
- Magnet
- VELO
- RICH1
- RICH2
- Calorimeters
- Muon System
- 20 m
2. LHCb re-optimization

Re-optimization of LHCb detector (TDR Sept. 2003)

“LHCb Classic”:

“LHCb Lite”:
2. LHCb re-optimized detector

- Reduced number of layers for Muon Station M1 (4 → 2)
- Reduction in total number of tracking stations: (9 → 4)
- No tracking chambers in the magnet
- No B field shielding plate
- Full Si station upstream magnet
- RICH-1 design: vertical, two mirrors
- Reduced number of VELO stations (25 → 21)
- Beam-pipe made out of Be and Al-Be alloy sections

- Material budget: reduced from 0.6$X_0$ (0.2$\Lambda_1$) to 0.4$X_0$ (0.12$\Lambda_1$) upstream of RICH2
- Efficiency for 5 prong events (e.g. $B_s \rightarrow D_s K$) had reduced considerably due to material
- Inclusion of B-field between VELO and TT allows to include transverse momentum in trigger → RICH1 needed to be redesigned.

Changes were made for **material reduction** and **L1 trigger improvement**
2.1 Magnet

Warm dipole magnet:

\[ \int B \cdot dl = 4 \ T \cdot m \]

Current: 6000 A
Yoke: 1500 tonnes

Commissioned November 04
Field map measurements completed

Construction completed
2.2 VELO

- 21 stations, retractable during injection
- Sensitive area starts at only 8 mm from beam axis
- $r/\phi$ sensors (single sided, 45° sectors).
- Pitch ranges from 37 $\mu$m to 103 $\mu$m.
- 300 $\mu$m thick silicon.
- 180k readout channels

stand-alone tracking!
2.2 VELO

- VELO will not survive radiation environment beyond 3 years data taking
- Studies underway to search for a VELO upgrade
- Workshop at Imperial College on 1st April 2005
- Can LHCb cope with increased luminosity?
- Radiation hard VELO options:
  - Czochralski silicon (high O₂ content)
  - n-on-p Si
  - 3D detectors

- Improve LHCb trigger, using pixel detector?
2.3 Particle Identification

- Excellent Particle Identification ($\pi$-K separation) required from 1 - 150 GeV/c

- RICH system divided into 2 detectors and 3 radiators: aerogel, $C_4F_{10}$, CF$_4$
2.3 RICH Detectors

RICH1
Acceptance 25-300 mrad

y-z view

(a) x-z view

RICH2
Acceptance 15-120 mrad

Note Scale Difference

(Beryllium)

Mostly UK responsibility

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2.3 RICH1

- Requirement for Level-1 trigger
  - Bending VELO – TT: > 0.15 T·m
- Shielding of MaPMT
  - Axial field < 25 G
  - Transverse field < 200 G

Vertical RICH1 seals to VELO

Photoelectron det. eff. vs axial B-field (mT)

Level-1 trigger performance

integrated B field (0 < z < 250) (Tm)

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2.3 RICH2 and HPD

- RICH2 structure constructed (UK respons.)
- Choice of photon detector for RICH detectors: Pixel Hybrid PhotoDiodes (pixel HPD)

- 8192 pixels: 62.5µm x 500µm
- 1024 super-pixels: 0.5mm x 0.5mm

Photon detector plane

9 HPDs in test beam
2.3 RICH radiators

Cherenkov angle: \( \cos(\theta_c) = \frac{1}{n \cdot v/c} \)

Aerogel:

Three radiators provide excellent \( \pi/K \) separation from 2-100 GeV

<table>
<thead>
<tr>
<th></th>
<th>Aerogel</th>
<th>( C_4F_{10} )</th>
<th>CF(_4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>L</td>
<td>50</td>
<td>850</td>
<td>1670 mm</td>
</tr>
<tr>
<td>n</td>
<td>1.03</td>
<td>1.0014</td>
<td>1.0005</td>
</tr>
<tr>
<td>( \theta_c ) max</td>
<td>242 mrad</td>
<td>53 mrad</td>
<td>32 mrad</td>
</tr>
<tr>
<td>( \pi )</td>
<td>0.6</td>
<td>2.6</td>
<td>4.4 GeV/c</td>
</tr>
<tr>
<td>K</td>
<td>2.0</td>
<td>9.3</td>
<td>15.6 GeV/c</td>
</tr>
</tbody>
</table>
2.3 Reconstructed rings

Cherenkov Rings:

- **RICH1**
  - C$_4$F$_{10}$ (small)
  - Aerogel (large)

- **RICH2**
  - CF$_4$
2.3 Hadron particle identification

- Full global ring pattern recognition
  - Use info from all reconstructed tracks traversing the RICHes
  - Determine for each track log-likelihood differences between two hypotheses, e.g. $\Delta \ln L_{K\pi} = \ln L(K) - \ln L(\pi)$
- Can cut on $\Delta \ln L$ values depending on analysis
- Example of performance:

  $\varepsilon(K \to K) = 88\%$, $\varepsilon(\pi \to K) = 2.9\%$, for $\Delta \ln L_{K\pi} > 2$
  $\varepsilon(K \to K) = 85\%$, $\varepsilon(\pi \to K) = 1.7\%$, for $\Delta \ln L_{K\pi} > 4$

(long tracks between 2 and 100 GeV)
2.3 RICH performance

Background rejection with RICH

**No RICH**

- $B_s \to KK$ (purity 13%)
- $B_s \to D_s K$ (purity 7%)

**With RICH**

- $B_s \to KK$ (purity 84% efficiency 79%)
- $B_s \to D_s K$ (purity 67% efficiency 89%)

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2.4 Silicon and Gas trackers

- Silicon tracker: inner section of tracking stations T1-T3 and Trigger Tracker (TT) upstream of magnet
- Outer tracker region: straw tubes.

- High-flux region (2%): Si detector (Inner Tracker)
- Remaining area (98%): straw drift-tubes (Outer Tracker)
2.4 Tracking

Long tracks ⇒ highest quality for physics (good IP & p resolution)
Downstream tracks ⇒ needed for efficient K_s finding (good p resolution)
Upstream tracks ⇒ lower p, worse p resolution, but useful for RICH1 pattern recognition
T tracks ⇒ useful for RICH2 pattern recognition
VELO tracks ⇒ useful for primary vertex reconstruction (good IP resolution)
2.4 Result of track finding

Typical event display:
Red = measurements (hits)
Blue = all reconstructed tracks

<table>
<thead>
<tr>
<th>Average multiplicity in bb event</th>
<th>\langle \delta p/p \rangle</th>
<th>efficiency</th>
<th>\sigma (IP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>26 long tracks</td>
<td>0.37%</td>
<td>94% for p &gt; 10 GeV/c</td>
<td>40 \mu m</td>
</tr>
<tr>
<td>4 downstream tracks</td>
<td>0.43%</td>
<td>80% for p &gt; 5 GeV/c</td>
<td></td>
</tr>
<tr>
<td>11 upstream tracks</td>
<td>~15%</td>
<td>75% for p &gt; 1 GeV/c</td>
<td></td>
</tr>
<tr>
<td>5 T tracks</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>26 VELO tracks</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total = 72 tracks</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

20–50 hits assigned to a long track
98.7% correctly assigned
2.4 Tracking and vertexing

Track efficiency vs p (GeV/c):
$\varepsilon = 94\%$ for $p > 10$ GeV
(larger for tracks from B)

Fraction ghost tracks vs minimum $p_T$ cut (GeV):

$3\%$ for $p_{T,\text{cut}} = 0.3$ GeV
(B tracks have large $p_T$)

Vertex: use long, upstream and VELO tracks→vertex found in 98% of bb events

No problem multiple vertices
2.5 Calorimeters

ECAL: 3312 “shashlik” modules

- 66 layers of 2mm Pb/4mm scintillator read out via WLS fibers

HCAL modules

- 1468 channels, longitudinal-tiles
- 6mm master/4mm spacer
- 3mm scintillator with WLS fibers

PS and SPD

- 2.5 X0 lead converter
- sandwiched between two scintillator planes with 2x5952 scintillating pads

Module 0.5x0.5m²
2.5 Calorimeter performance

- $\gamma$ with high $E_T (> 2−3$ GeV):
  - easy to trigger
  - used to reconstruct radiative B decays such as $B^0 \rightarrow K^*\gamma$ and $B_s \rightarrow \phi\gamma$
  - $\gamma$ pairs from hard $\pi^0$ can “merge” and be reconstructed as single $\gamma$

- Resolved $\pi^0$ (2 $\gamma$ clusters):
  - $\sigma(m_{\gamma\gamma}) \sim 10$ MeV

- Merged $\pi^0$ (single cluster):
  - core $\sigma(m) \sim 15$ MeV
  - Larger $p_T(\pi^0)$ $\rightarrow$ less comb. bkg.

-- B$^0 \rightarrow K^{*\gamma}$ signal
\[\sigma \sim 65$ MeV\]

-- Resolved $\pi^0$ ($2 \gamma$ clusters):
\[\sigma(m_{\gamma\gamma}) \sim 10$ MeV\]

-- Merged $\pi^0$ (single cluster):
\[\sigma(m) \sim 15$ MeV\]
\[\sigma \sim 75$ MeV\]
\[\text{same resolution as with resolved } \pi^0\]
2.6 Muon system

First muon station (M1): Triple GEM detectors due to high particle rate

Other muon stations: MWPC
2.6 Combined PID Mu/Calo

- Build combined $\Delta \ln L$ variables using information from muon detector, calorimeters, and RICHes
  $\Rightarrow$ both muon and electron ID significantly improved

$\mu$

with muon detector info

$\pi$

with muon detector info (~3%)

$\varepsilon(\mu \rightarrow \mu) = 93\%$, $\varepsilon(\pi \rightarrow \mu) = 1\%$

$\varepsilon(e \rightarrow e) = 95\%$, $\varepsilon(\pi \rightarrow e) = 0.7\%$

$p_{\mu} > 3$ GeV and in MUON acceptance

e from $B^{0} \rightarrow J/\psi K_{S}$ in CALO acceptance
2.6 $J/\psi \rightarrow l^+l^-$ reconstruction

- $B_s \rightarrow J/\psi(l^+l^-)\phi(K^+K^-)$ events
- Select all $J/\psi$ candidates
- For electrons, add energy of Bremsstrahlung before magnet:
  \[ E_0 = E_1 + E_2 \]

\[ \sigma = 15 \text{ MeV} \]
\[ \sigma \sim 60 \text{ MeV} \]

- real electrons (including imperfect Bremsstrahlung correction)
- + ghost (mainly low $p_T$)
### 2.7 Trigger

**Three Trigger Levels:**

- **L0**: fully synchronous and pipelined:
  - Pile-Up
  - Calorimeter
  - Muon
  - L0 decision unit

- **L1**: software trigger
  - VELO
  - TT
  - L0-objects

- **HLT**: software trigger
  - Access to all sub-detectors
2.7 Trigger rates

Level-0 (hardware)
- Level-0: synchronous
  - 30 MHz pp crossings
  - 10 MHz “visible” @ 2.10^{32}
  - L0 Multiplicity/Pile-up: 7 MHz
  - High $E_T$ trigger (Muon + Calorimeter system): 1 MHz

Level-1: 1 ms
- VELO: impact parameter
- VELO+TT: $P_T$ trigger
- VELO+L0+Muon: $\mu$, $\mu\mu$, $J/\Psi$
- $L0_{\text{bonus}} + p_T + \text{impact}$: 40 kHz

HLT: 10 ms
- L1(VELO+TT)+T: 12 kHz
- VELO+TT+T: $dp/p<1\%$ full reconstruction: 200 Hz

Algorithms still being optimised
3. Physics

- MC Pythia 6.2 tuned on CDF and UA5 data
- Multiple pp interactions and spill-over effects included
- Complete pattern recognition in reconstruction
3.1 Physics: $B_s$ oscillation

- Needed for the observation of CP asymmetries with $B_s$ decays
- Use $B_s \rightarrow D_s^{-} \pi^+$
- If $\Delta m_s = 20$ ps$^{-1}$

$\sigma(\Delta m_s) = 0.011$ ps$^{-1}$

- Can observe $>5\sigma$ oscillation signal if $\Delta m_s < 68$ ps$^{-1}$ well beyond SM prediction

Expected unmixed $B_s \rightarrow D_s^{-} \pi^+$ sample in one year of data taking (fast MC)

Full MC

$\Delta m_s = 25$ ps$^{-1}$

Proper-time resolution plays a crucial role
3.2 $\sin 2\beta$

Measurement of $\sin(2\beta)$: golden decay mode

$$A_{CP}(t) = \frac{\Gamma_f - \overline{\Gamma}_f}{\Gamma_f + \overline{\Gamma}_f} = A^{\text{dir}} \cos(\Delta M t) + A^{\text{int}} \sin(\Delta M t)$$

$$A_{CP}(t) = -\text{Im}\{\lambda\}\sin(\Delta M t)$$

$$\lambda = \left(\frac{q}{p}\right)_{B_d^0} \left(\frac{q}{p}\right)_{K^0} \left(\frac{A}{J/\psi K_s^0}\right) = -\left(\frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*} \frac{V_{cs} V_{cd}^*}{V_{cs}^* V_{cd}} \frac{V_{cb} V_{cs}^*}{V_{cb}^* V_{cs}}\right) = -\frac{|V_{td}| e^{-i\beta}}{|V_{td}| e^{i\beta}} = -e^{-2i\beta}$$

$$\text{Im}\{\lambda\} = \text{Im}\{-e^{-2i\beta}\} = \sin 2\beta$$

BaBar and Belle:

$$\sin 2\beta = 0.722 \pm 0.040 \pm 0.023 \quad \text{Babar 227M} \quad \overline{\text{BB}}$$

$$\sin 2\beta = 0.728 \pm 0.056 \pm 0.023 \quad \text{Belle 152M} \quad \overline{\text{BB}}$$

$$\sin 2\beta = 0.726 \pm 0.037 \quad \text{Average}$$
### 3.2 Sin 2β (B^0 → J/ψ(μμ)K_S)

#### Background-subtracted B^0 → J/ψ(μμ)K_S CP asymmetry after one year

**ACP(t)**

-0.8  -0.6  -0.4  -0.2  0  0.2

**0** **1** **2** **3** **4** **5** **6** **7** **8** **9** **10**

**w = 34.3%**

σ_M = 11.1 ± 0.2 MeV/c^2

B_d → J/ψ K_s^0

σ(sin(2β)) = 0.022

(after 1 year)

- Theoretically clean
- High statistics to fit A_{dir}: ~ 10^5 events/year
- B mass resolution = 11 MeV
- B time resolution = 36 fs

\[ A_{CP} = A_{dir} \cos(\Delta m_d t) + A_{mix} \sin(\Delta m_d t) \]

If \( A_{dir} \neq 0 \) then it could be evidence for new physics.
3.3 \sin(2\chi) from B_s \rightarrow J/\Psi \Phi

B_s Mixing Phase: probe of new physics

- Channel: B_s \rightarrow J/\Psi \Phi
- Expect \sim 100K (32k tagged) events
- Negligible background
- Final state not CP eigenstate

\[ A_{CP}(t) = \frac{\Gamma_f - \overline{\Gamma_f}}{\Gamma_f + \overline{\Gamma_f}} = A^\text{dir} \cos(\Delta M t) + A^\text{int} \sin(\Delta M t) \]

\[ A_{CP}(t) = -\text{Im}\{\lambda\}\sin(\Delta M t) \]

\[ \lambda = \left( \frac{q}{p} \right)_{B_s^0} \frac{A}{A} = \left( \frac{V_{tb}^* V_{ts}}{V_{tb} V_{ts}^*} \right) \left( \frac{V_{cb} V_{cs}^*}{V_{cb}^* V_{cs}} \right) \]

\[ \text{Im}\{\lambda\} = \text{Im}\{e^{2i\chi}\} = \sin 2\chi \]

- \sigma(\sin 2\chi) \sim 0.05–0.06 (1 year), 0.03 (5 years)
- Standard Model: \sin 2\chi = -\eta \lambda^2 \sim 0.04
3.4 $2\beta+\gamma$ from $B_d \to D^*\pi$

- Non-CP eigenstates
- Tree diagrams only → theoretically clean

\[
\lambda = \begin{pmatrix} \frac{q}{p} \\ \frac{A_{B_d}}{A} \end{pmatrix}_{B_d \to D^*\pi^-} = \begin{pmatrix} V_{tb}V_{td} \\ V_{tb}V_{td}^* V_{cb}V_{ud} \end{pmatrix} \begin{pmatrix} T_1 \\ T_2 \end{pmatrix} e^{i\Delta \delta}
\]

\[
\text{arg}\{\lambda\} = -2\beta - \gamma - \Delta \delta
\]

\[
\overline{\lambda} = \begin{pmatrix} \frac{p}{q} \\ \frac{\overline{A}_{B_d}}{\overline{A}} \end{pmatrix}_{B_d \to D^-\pi^+} = \begin{pmatrix} V_{tb}V_{td}^* \\ V_{tb}V_{td} V_{ub}V_{cd} \end{pmatrix} \begin{pmatrix} T_1 \\ T_2 \end{pmatrix} e^{i\Delta \delta}
\]

\[
\text{arg}\{\overline{\lambda}\} = 2\beta + \gamma - \Delta \delta
\]
3.4 $2\beta+\gamma$ from $B_d \rightarrow D^*\pi$

Fit time-dependent asymmetries

Exclusive $B_d \rightarrow D^*\pi$

$$|\xi|\sigma / |\xi|= 0\%$$

$$|\xi|\sigma / |\xi|= 10\%$$

$$\sigma(2\beta+\gamma)$$

$$A_{D^-}(t) = \frac{\Gamma(B_d \rightarrow D^-\pi^+) - \Gamma(B_d \rightarrow D^-\pi^+)}{\Gamma(B_d \rightarrow D^-\pi^+) + \Gamma(B_d \rightarrow D^-\pi^+)}$$

$$A_{D^+}(t) = \frac{\Gamma(B_d \rightarrow D^+\pi^-) - \Gamma(B_d \rightarrow D^+\pi^-)}{\Gamma(B_d \rightarrow D^+\pi^-) + \Gamma(B_d \rightarrow D^+\pi^-)}$$

$\delta=0^\circ$

Seminar, Royal Holloway
13 April 2005
3.4 $\gamma - 2\chi$ from $B_s \rightarrow D_s^{\mp}K^\pm$

- $B_s^0$ analogue of $B_d^0 \rightarrow D^*\pi$
- Non-CP eigenstates
- Tree diagrams only $\rightarrow$ theoretically clean

Measure 2 time dependent asymmetries from 4 decay rates

$$B_s^0 \left( \bar{B}_s^0 \right) \rightarrow D_s^- K^+, D_s^+ K^-$$

Background reduction from $D_s \pi$ with RICH

$$\arg \{ \lambda \} = -\gamma + 2\chi + \Delta \delta$$
$$\arg \{ \bar{\lambda} \} = \gamma - 2\chi + \Delta \delta$$

Suppress with RICH: final $D_s \pi$ contamination $\sim 10\%$
3.4 $\gamma - 2\chi$ from $B_s \rightarrow D_s^{\mp}K^\pm$

Rate asymmetries measure angle $\gamma + \Phi_s = \gamma - 2\chi$

Proper time: 44 fs, B mass: 11 MeV

Expect $\sim 5400$ $B_s \rightarrow D_s(KK\pi)K$ events/year

$$A_{\text{CP}}(D_s^{\mp}K^-) \equiv \frac{B_s^0 \rightarrow D_s^{+}K^- - \overline{B}_s^0 \rightarrow D_s^{-}K^-}{B_s^0 \rightarrow D_s^{+}K^- + \overline{B}_s^0 \rightarrow D_s^{-}K^-}$$

$$= \frac{C_s \cos \Delta m_s t + S_s \sin \Delta m_s t}{\cosh(\Delta \Gamma_s t/2) - A_{\Delta \Gamma} \sinh(\Delta \Gamma_s t/2)}$$

$$C_s = -\left(\frac{1-r_s^2}{1+r_s^2}\right) \quad S_s = \frac{2r_s \sin(\Phi_s + \gamma + \delta_s)}{1+r_s^2}$$

$$A_{\Delta \Gamma} = -\frac{2r_s \cos(\Phi_s + \gamma + \delta_s)}{1+r_s^2}$$

$\sigma(\gamma) \sim 10^0$ for $\Delta m_s = 20$ ps$^{-1}$

$\sigma(\gamma) \sim 15^0$ for $\Delta m_s = 30$ ps$^{-1}$
3.4 $\gamma$ from $B_s \rightarrow D_s K$ and $B_d \rightarrow D^* \pi$

- But … there is an eight-fold ambiguity in $\gamma$ from $B_d \rightarrow D^* \pi$ and $B_s \rightarrow D_s K$
- Use tagged/untagged or U-spin symmetry (Fleischer, NPB 671 (2003), 459).

- Perfect U-spin
- $\pm 20\%$ breaking
- Statistical precision $\approx 5$ degrees
- U-spin systematic $\approx 3$ degrees

(in this example!)
3.4 $\gamma$ from $B \rightarrow D K^*$

- Application of Gronau-Wyler method (Dunietz): tree diagrams only
- Theoretically clean
- Sensitive to new physics in $D^0$-$D^0$ oscillations

**Example**

$B^0_d \rightarrow D^0 K^{*0}$

Measure 6 time-integrated decay rates

- **(A3)**
  - $B_d \rightarrow D^0 K^{*0}$, $B_d \rightarrow D^0 K^{*0}$, $B_d \rightarrow D^0 K^{*0}$
- **(A1)**
  - $B_d \rightarrow D^0 K^{*0}$, $B_d \rightarrow D^0 K^{*0}$, $B_d \rightarrow D^0 K^{*0}$
- **(A2)**
  - $B_d \rightarrow D^0 K^{*0}$, $B_d \rightarrow D^0 K^{*0}$, $B_d \rightarrow D^0 K^{*0}$

**Yield**

<table>
<thead>
<tr>
<th>Mode</th>
<th>Yield</th>
<th>S/B</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0 \rightarrow D^0 (K^+\pi^-) K^{*0}$</td>
<td>3400</td>
<td>&gt; 3.3</td>
</tr>
<tr>
<td>$B^0 \rightarrow \bar{D}^0 (K^+\pi^-) K^{*0}$</td>
<td>500</td>
<td>&gt; 0.6</td>
</tr>
<tr>
<td>$B^0 \rightarrow D^0_{CP} (K^+K^-) K^{*0}$</td>
<td>600</td>
<td>&gt; 0.7</td>
</tr>
</tbody>
</table>

Sensitivities per year: $\sigma(\gamma) \sim O(8^0)$
3.4 $\gamma$ from $B \rightarrow \pi\pi, KK$

Measure time-dependent CP asymmetries to extract $A_{CP}^{dir}$ and $A_{CP}^{mix}$

$$A_{CP}^{th}(\tau) = \frac{A_{CP}^{dir} \cdot \cos(\Delta M \cdot \tau) + A_{CP}^{mix} \cdot \sin(\Delta M \cdot \tau)}{\cosh\left(\frac{\Delta \Gamma}{2} \cdot \tau\right) - A_{\Delta \Gamma} \cdot \sinh\left(\frac{\Delta \Gamma}{2} \cdot \tau\right)}$$

$\sigma(A_{CP}^{dir}) \simeq 0.07$

$\sigma(A_{CP}^{mix}) \simeq 0.06$

$sensitivity in 1 year$

$\text{Corr} (A_{CP}^{dir}, A_{CP}^{mix}) \simeq -0.49$

$\sigma(A_{CP}^{dir}) \equiv \sigma(A_{CP}^{mix}) \simeq 0.04$

$\text{Corr} (A_{CP}^{dir}, A_{CP}^{mix}) \equiv 0$

@ $\Delta \Gamma_s = 0 \quad \Delta M_s = 14 \text{ ps}^{-1}$
3.4 $\gamma$ from $B \to \pi\pi$, KK

- Method proposed by R. Fleischer: $b \to u$ processes, with large $b \to d(s)$ penguin contributions

  - SM predictions:
    
    $A_{\text{dir}}(B^0 \to \pi^+\pi^-) = f_1(d, \vartheta, \gamma)$
    $A_{\text{mix}}(B^0 \to \pi^+\pi^-) = f_2(d, \vartheta, \gamma, \phi_d)$
    $A_{\text{dir}}(B_s \to K^+K^-) = f_3(d', \vartheta', \gamma)$
    $A_{\text{mix}}(B_s \to K^+K^-) = f_4(d', \vartheta', \gamma, \phi_s)$

  - Assuming U-spin flavour symmetry (interchange of $d$ and $s$ quarks):
    
    $d = d'$ and $\vartheta = \vartheta'$

  - 4 measurements (CP asymmetries) and 3 unknown ($\gamma$, $d$ and $\vartheta$) → can solve for $\gamma$

    | years | 1     | 2     | 3     | 4     |
    |-------|-------|-------|-------|-------|
    | $\sigma(\gamma)$ | 5.5°  | 3.3°  | 2.6°  | 2.2°  |

$\gamma$ (degrees)

95% confidence region for $d$ and $\gamma$

- $d \exp(i \vartheta) = $ function of tree and penguin amplitudes in $B^0 \to \pi^+\pi^-$
- $d' \exp(i \vartheta') = $ function of tree and penguin amplitudes in $B_s \to K^+K^-$
3.4 $\gamma$ from $B\to\pi K$

- Exploit isospin flavour symmetry
- Large penguin contributions
- Sensitive to new physics
- Dependent on hadronic assumptions in the calculations
- Reduce isospin breaking effects using QCD factorization

**Observables**

\[
R \equiv \frac{B(B_d \to \pi^- K^+) + B(B_d^* \to \pi^+ K^-)}{B(B^+ \to \pi^+ K^0) + B(B^- \to \pi^- \bar{K}^0)}
\]

\[
A_0 \equiv \frac{B(B_d \to \pi^- K^+) - B(B_d^* \to \pi^+ K^-)}{B(B^+ \to \pi^+ K^0) + B(B^- \to \pi^- \bar{K}^0)}
\]

Requires knowledge of trigger and reconstruction efficiencies for different final states.
3.5 $\alpha$ from $B_d \rightarrow \pi^- \pi^+$

- Large penguin contribution
  
  - Either input penguin and tree amplitudes and strong phases
  - Or extract $\alpha$ from $\alpha_{\text{eff}}$ using amplitude relations
    (difficult at LHC)

$$\sin 2\alpha_{\text{eff}} = 0.02 \pm 0.34 \pm 0.05$$

with $2\alpha_{\text{eff}} = 2\alpha + \Box$

Isospin analysis
Gronau-Wyler
3.5 $\alpha$ from $B_d \rightarrow \pi^- \pi^+$

- Backgrounds similar topology

\[ Br(B_d^0 \rightarrow K^\pm \pi^\mp) = (1.74 \pm 0.15) \times 10^{-5} \]
\[ Br(B_d^0 \rightarrow \pi^\pm \pi^\mp) = (0.44 \pm 0.09) \times 10^{-5} \]

- Without RICH: $\sigma \sim 70$ MeV/$c^2$

- With RICH: $\sigma \sim 17$ MeV/$c^2$
Sensitivity to $\alpha$

$A_{CP}(t) = A^{dir} \cos(\Delta M t) + A^{int} \sin(\Delta M t)$

$A^{dir} = 2 \left| \frac{P}{T} \right| \sin \delta \sin \alpha$

$A^{int} = -\sin(2\alpha) - 2 \left| \frac{P}{T} \right| \cos \delta \cos(2\alpha) \sin \alpha$

4-fold discrete ambiguity in $\alpha$

Sensitivity to $\alpha$ could be limited after 1 year if $|P/T|$ is not known better than 10%.
3.6 Rare decays

- $B_s \rightarrow \mu^+\mu^-$
  - Standard Model branching ratio: $3.7 \times 10^{-9}$
  - Ideal to search for new physics - FCNC
  - Combine with $B_d \rightarrow \mu^+\mu^-$ to obtain $|V_{td}/V_{ts}|^2$
  - Expected signal (bkgd): 11 (3.3) 1 year

- $B_d \rightarrow K^*\mu^+\mu^-$
  - Standard Model branching ratio: $1.5 \times 10^{-6}$
    - Dimuon mass spectrum, forward-backward asymmetry
    - Combine with $B_d \rightarrow \rho \mu^+\mu^-$
    - Expected signal (bkgd): 22400 (1400) 1 year

- $B_d \rightarrow K^*\gamma$
  - Standard Model branching ratio: $5 \times 10^{-5}$
    - Search for new physics in asymmetry $\delta_{CP} \sim 1\%$ in SM
    - Expected signal: 26000 1 year
Conclusions

- Possible scenario in 2007 (pre-LHCb):

- After 1 year LHCb measurements. Maybe …
Conclusions

- Extract new physics contribution?
Conclusions

- Physics performance of re-optimized LHCb detector can measure all parameters of unitarity triangle in more than one manner
- Progress in the LHCb detector construction is very good and is on-track to take data when LHC becomes operational in April 2007