PROSPECTS FOR CP VIOLATION MEASUREMENTS IN LHCb

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At day 1 of LHCb (2005):

Will have provided:

- accurate measurements of $|V_{cb}|$, $|V_{ub}|$, $|V_{td}|$,
  rare B decays channels, perhaps $\Delta m_s$
- $\sin(2\beta)$ from $B_d \rightarrow J/\psi K_s$ with $\sigma \leq 0.05$

signals of New Physics or agreement with Standard Model?

precise measurements of all Unitarity Triangles parameters will be
required to get more informations and to over constrain the UT

### Few examples:

- $B^0_d \rightarrow J/\psi K^0_s$:
  
  $A_{CP} (t) = A_{\text{dir}} \cos (\Delta m t) + A_{\text{mix}} \sin (\Delta m t)$

  high statistics is necessary to have sensitivity on $A_{\text{dir}}$

  \text{(LHCb 1 year's data)}

\[ \sigma_{\sin 2\beta} = 0.021 \]
New Physics
in $B^0\overline{B}^0$ mixing?

Both $B^0$ oscillations and $B^0_d \rightarrow J/\psi K^0_s$ asymmetry would be affected: $\beta$ measurements biased

From CP asymmetry in $B^0_d \rightarrow D^* \pi^\pm$: $-2\beta + \Phi_{NP} - \gamma$

Subtracting from $B^0_d \rightarrow J/\psi K^0_s$: $-2\beta + \Phi_{NP}$

A clean determination of $\gamma$ and a test of New Physics

Experimental requirements:

- High statistics on $B_d$ and $B_s$ to reach channels with small BR's ($< 10^{-7}$)
- Measure rapid $B_s$ oscillations: good proper time resolution
- Good efficiency on several final states, including hadronic multi-body:
  - Sensitive trigger (leptonic and hadronic final states)
  - Particle identification
  - Good mass resolution
**B production at LHC**

pp collisions at $\sqrt{s} = 14$ TeV:

- $\sigma_{\text{inel}} \approx 80$ mb
- $\sigma_{b\bar{b}} \approx 500$ $\mu$b
- $S/B \sim 1\%$

★ **Forward production of $b\bar{b}$, correlated**

Good acceptance in single arm forward spectrometer

LHCb: $15$ mrad $< \theta < 300$ mrad $(1.9 < \eta < 4.9)$

★ **Several pp interactions per bunch crossing**

LHCb chooses to work with single interaction

Advantages for: radiation damage
detector occupancy
triggering
pattern recognition, flavour tagging
The detector will be operated at \( L \sim 2 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1} \)
- beams defocused at LHCb interaction point
- compatible with LHC running @ \( 10^{34} \text{ cm}^{-2} \text{ s}^{-1} \)

\[ \rightarrow 10^{12} \overline{b}b \text{ events / year} \]

★ Charged particle multiplicity

New tuning of simulation on UA5, CDF data after LHCb Technical Proposal:
\((\text{PYTHIA 6.1, multiple parton-parton interaction model, CTEQ4L structure function “post-HERA”})\)

but TRIGGER performances are not affected!
LHCb Milestones

- Feb 1996  LHCb Letter of Intent
- Sep 1998  Approval of Technical Proposal
  - Magnet  TDR approved April 2000
  - Vertex Locator  TDR April 2001
  - Inner Tracker  TDR September 2001
  - Outer Tracker  TDR March 2001
  - RICH System  TDR submitted 7 September 2000
  - Calorimeter System  TDR submitted 6 September 2000
  - Muon System  TDR January 2001
  - Trigger  TDR January 2002
  - Computing  TDR July 2002

- 2000- July 2004  Construction Phase
- July 2005  1st beam in LHCb
**GOALS:**

- **LHCb TRIGGER**

  - 40 MHz trigger, robust and flexible (not relying on a single subdetector)
  - Efficient on several B decay topologies (also fully hadronic final states)

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**Level 0**

- 40 MHz
- 4 µs
- 60 k channels

- pile up veto
- high $p_t$ muons ($p_t > 1$ GeV/c)
- high $p_t$ electrons, photons and hadrons ($p_t > 2.4, 3.4$ GeV/c)
  - (reduction factor = 10 from high $p_t$)

**Level 1**

- 1 MHz
- 1 ms
- 220 k channels

- identify secondary vertices

**Level 2**

- 40 kHz

- refine secondary vertices
- adding momentum information

**Level 3**

- 200 Hz

- offline algorithms,
- final states reconstruction

*to tape (~ 20 Mbyte/s)*

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**Full event read-out and event building**

- Pile up vertex detector
- Muon system
- Calorimeter system
- VErtex LOcator
- VELO, first tracking chambers
- Full detector

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TRIGGER Efficiency

<table>
<thead>
<tr>
<th></th>
<th>L0(%)</th>
<th>L1(%)</th>
<th>L2(%)</th>
<th>Total(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_d \rightarrow J/\psi (e,e) K_S$ + tag</td>
<td>72</td>
<td>42</td>
<td>81</td>
<td>24</td>
</tr>
<tr>
<td>$B_d \rightarrow J/\psi (\mu\mu) K_S$ + tag</td>
<td>88</td>
<td>50</td>
<td>81</td>
<td>36</td>
</tr>
<tr>
<td>$B_s \rightarrow D_S K$ + tag</td>
<td>54</td>
<td>56</td>
<td>92</td>
<td>28</td>
</tr>
<tr>
<td>$B_d \rightarrow \pi\pi$ + tag</td>
<td>76</td>
<td>48</td>
<td>83</td>
<td>30</td>
</tr>
<tr>
<td>$B_d \rightarrow D_S K^*0$</td>
<td>37</td>
<td>59</td>
<td>95</td>
<td>21</td>
</tr>
</tbody>
</table>

for reconstructed and correctly tagged events

Future improvements of L1:
will take into account L0 informations
to form a new decision
will increase efficiency, e.g. in $\mu\mu$ channels
triggering on 2 high-p$_t$ muons
Vertex Locator (VELO)

*Silicon strip detector in LHCb vacuum chamber*
- 17 stations with R and $\phi$ measuring planes
- sensitive area $10 \text{ mm} < r < 60 \text{ mm}$
- 2 half disks: retracted during injection by 3 cm to reduce radiation damage

*Optimization for TDR:*
- # of stations (25), positions, outer & inner radii
- on average 9.5 hits / track

- Strips segmentation and pitch ($40 \mu\text{m} - 105 \mu\text{m}$) determined by occupancy:
  
  always below 1%

- Number of readout channels = $2.2 \times 10^5$
**Vertex Locator (VELO)**

- Single sided 200 µm Si, double metal read out:
  - Thin detector
  - $S/B \sim 12$

- Impact parameter resolution:
  - Accuracy on primary vertex: 40 µm

- Front-end chip: 2 options under development (DMILL SCTA128 or sub micron BEETLE)

Prototype detector with 3 R and 3 φ sectors
Proper time resolution for $B_s \rightarrow D_s \pi$

* time-dependent asymmetry measurements
* oscillations measurements

$\sigma_\tau \sim 43 \text{ fs}$

$> 5 \sigma$ measurement for $\Delta m_s \leq 48 \text{ ps}^{-1}$ ($x_s = 75$)
MAGNET

warm dipole 4 Tm (4.2 MW, yoke 1450 t)

MAIN TRACKER

OUTER TRACKER: straw drift tubes
INNER TRACKER: triple GEM with 2D readout
Si strips

σp / p = 0.3%
5 GeV/c < p < 200 GeV/c

σ (M) = 17 MeV for B_d → π^+π^-
σ (M) = 4 MeV for D_s → K^-K^+π^-

TDR approved april 2000
Hadron identification in LHCb:

- **Background suppression**
  - high momentum hadrons in two-body B decays

- **B flavour tag**
  - identify K from $b \to c \to s$
  - low momentum hadrons

2 RICH detectors with 3 radiators
more than $3\sigma$ $\pi / K$ separation in $3 < p < 100$ GeV/c
RICH PHOTODETECTORS

Requirements: ~ 3 m² area, 2.5×2.5 mm² granularity, single photon sensitivity, high Q.E.

3 options considered:
- **Pixel HPD**  
  - base line solution
- **Pad HPD**
- **MaPMT**  
  - backup solution

Pixel Hybrid PhotoDiode  
[ CERN and DEP (The Nederlands) project ]

- 1024 (500µm×500µm) Si pixel sensor bump bonded to binary read out electronics - ALICE chip
- ∫Q.E. dE ~ 0.77 eV
- 80 mm diameter envelope cross-focusing electrodes
- 70% active area coverage  
  (~450 tubes, ~325 k channels)
TEST BEAM RESULTS

61-pixel HPD (80 mm)

Full scale RICH 1 prototype

Accumulated Cherenkov rings

Aerogel test

+ 8 GeV/c beam: $\pi$ and protons

Accumulated Cherenkov rings on two pad HPD (2048 channels)
L0 trigger requires: fast detector with longitudinal segmentation for e/π separation (electrons up to 200 GeV, hadrons up to 300 GeV)

Hit density varies 2 order of magnitude over calorimeter surface:
variable lateral segmentation (3 zones in ECAL, 2 zones in HCAL)

Joint Calorimeter Test

**Pre-shower:** sandwich scintillator-Pb-scintillator $2X_0$

**ECAL:** Shashlik type $25X_0$

$\sigma(E)/E = 10\% / \sqrt{E} \oplus 1.5\%$

**HCAL:** Fe + scintillating tiles, $5.6\,\lambda_I$

$\sigma(E)/E = 80\% / \sqrt{E} \oplus 10\%$
MUON CHAMBERS

5 muon stations: 870 m² of detector area, 
  ~ 150 k physical channels,  ~ 26 k logical channels

Regions closer to the beam have stronger requirements for rate capability

- Rate \( \leq 1 \text{ kHz/cm}^2 \) (42% of Muon System)
  
  **RPC** with 2 gaps (double gap or 2 single gap ORed)

  *Test beam results*: time resolution of 1.3 ns, with efficiency >99% in 10 ns
  efficiency >95% at 1.8 kHz/cm²

- 1 kHz/cm² < Rate \( \leq 100 \text{ kHz/cm}^2 \) (58% of Muon System)
  
  **MWPC** with anode wire and/or cathode pad readout
  
  good ageing properties when operated with Ar/CO₂/CF₄ 40/50/10 mixture

  *Test beam results*: time resolution < 3 ns, with efficiency >99% in 20 ns
  good performances at rates > 100 kHz/cm²

- Rate > 100 kHz/cm² ( < 1% of Muon System )
  
  still under study
\[ \gamma \text{ from } B_d \rightarrow D^{*+} \pi^\pm \]

- CP asymmetries from interference between \( B_d \rightarrow D^{*-} \pi^+ \) and \( B_d \rightarrow B \rightarrow D^{*-} \pi^+ \) decays
- Tiny effect (~ 1%) due to double Cabibbo suppressed \( b \rightarrow u \) transition
- Extract \( 2\beta + \gamma \) from time dependent fit of CP asymmetries. No penguin contributions.

![Graph showing search for \( B \rightarrow D^{*+} \pi^\pm \) decays]

**exclusive reconstruction**
\[ \sim 84 \text{k ev/year} \quad \text{S/B} \sim 12 \]
(reconstructed and tagged)

**partial reconstruction**
\[ \sim 260 \text{k ev/year} \quad \text{S/B} \sim 3 \]

\[ \sigma(2\beta + \gamma) \]

\[ \phi + \gamma \]

Sensitivity will depend on strong phase difference

\[ \sigma(\gamma) \sim 12^\circ \text{ in 1 year} \quad (\Delta_s = 0) \]

\( B_d \rightarrow D^{*+}a_1^{\pm} \) can be added \( \sim 360 \text{k events/year} \), \( \text{S/B} \sim 4 \).
\[ \gamma \text{ from } B_s^0 \rightarrow D_s^+ K^\pm \]

B_s counterpart of B_d \rightarrow D^{*-} \pi^+ but interference effects much larger. No penguins contributions.

Extract \( \gamma - 2\delta\gamma \) from time dependent fit of CP asymmetries.

Assuming \( 2\delta\gamma \) known from \( B_s \rightarrow J/\psi \phi \) this will be a clean measurement of \( \gamma \)

- Background from \( B_s^0 \rightarrow D_s^- \pi^+ \sim 20 \) times higher --> RICH for K/\pi separation (\( \pi \) misid 0.1%)
- Fast \( B_s \) oscillations --> good proper time resolution (VELO \( \sigma(\tau) = 43 \) fs)

2500 events expected in 1 year (reconstructed and tagged)

reconstr. efficiency 0.5 \%
\[ \sigma(M_B) \sim 11 \text{ MeV} \]
\[ S/B \sim 12.5 \]

Sensitivity to \( \gamma - 2\delta\gamma \) will depend on \( \Delta m_s, \Delta \Gamma_s / \Gamma_s \), strong phase difference:

expected precision \( \gamma - 2\delta\gamma : 6^\circ - 12^\circ (\Delta m_s = 15 \text{ ps}^{-1}) \)
Tree and Penguins parameters, including $\alpha$, can be extracted from a full 3 body analysis, taking into account interference effects between vector mesons of different charge.

$$\sigma(M_B) = 42 \text{ MeV}$$

(35 MeV with $\pi^0$ constraint)

Time dependent analysis of event distribution in Dalitz plot

**B$^0_d$** $\rightarrow$ $\rho^- \pi^+ \pi^- \pi^0$

**M$^2(\pi^+ \pi^- \pi^0)$**

expected events: $\sim 1200 \ \rho^\pm \pi^+$

$\sim 100 \ \rho^0 \pi^0$

**M$^2(\pi^+ \pi^0)$**

Expected sensitivity: $\sigma(\alpha) \sim 3^0 - 6^0$ in 1 year

LHCB
Expected CP sensitivities in 1 year *LHCb* *(10^7 s, L = 2 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1})*

<table>
<thead>
<tr>
<th>Decay channel</th>
<th>N events (reconstructed and tagged)</th>
<th>parameter</th>
<th>sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>(B^0_d \rightarrow J/\psi K_s)</td>
<td>100 k</td>
<td>(\sin(2\beta))</td>
<td>0.021</td>
</tr>
<tr>
<td>(B^0_d \rightarrow \pi^+ \pi^-)</td>
<td>5000</td>
<td>(\sin(2\alpha))</td>
<td>0.05 (No Penguins)</td>
</tr>
<tr>
<td>(B^0_d \rightarrow \rho \pi)</td>
<td>1300</td>
<td>(\alpha)</td>
<td>(\sim 5^\circ (\alpha=50^\circ))</td>
</tr>
<tr>
<td>(B_d \rightarrow D^{*-} \pi^\pm)</td>
<td>(84k) excl. (260k) incl.</td>
<td>(2\beta + \gamma)</td>
<td>(\sim 12^\circ (2\beta + \gamma=0, \Delta s=0))</td>
</tr>
<tr>
<td>(B^0_s \rightarrow D_s^+ K^\pm)</td>
<td>2400</td>
<td>(-2\delta\gamma + \gamma)</td>
<td>(8^\circ - 12^\circ (\Delta m_s=15-45 \text{ ps}^{-1}))</td>
</tr>
<tr>
<td>(B^0_s \rightarrow J/\psi \phi)</td>
<td>50 k</td>
<td>(\sin(2\delta\gamma))</td>
<td>0.03 ((\Delta m_s=25 \text{ ps}^{-1}))</td>
</tr>
</tbody>
</table>
CONCLUSIONS

- LHCb is rapidly evolving towards final design since TP.
  Major technology choices made.
  Magnet TDR approved, RICH and Calorymeter TDR submitted.
  Other Subsystem coming soon.

- Looking forward for “Ferrara 2005” for first LHCb results
  on new measurements of all UT angles with unparalleled precision
  and may be hints for new Physics beyond the Standard Model.