Status of LHCb detector optimization

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On behalf of the LHCb Collaboration
Tatsuya Nakada
CERN and University of Lausanne
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1) History of LHCb-light

Since Technical Proposal...

- **material budget** of the tracking detectors significantly increased
  (detector design became more realistic)
  - total $X_0$ in front of RICH2 increased from 40% to 60%
- **Level-1 trigger performance** dropped with the default algorithm
  default PYTHIA5.7 $\rightarrow$ tuned PYTHIA 6.2
  - higher multiplicities for L-0 triggered Min. Bias events
  - higher $c\bar{c}$ and b-baryon production rates

Technical Design Reports give a **solid base for the material budget**. PYTHIA is now tuned to reproduce Sp$\bar{p}$S and Tevatron multiplicity data.

$\Rightarrow$ **A good opportunity for re-optimization** to reduce material budget and to improve the trigger robustness.

started in late spring 2001
In the LHCb acceptance

minimum bias events

Pythia

TP

$m_{bias}$

$b$ events

$m_{bias}$

$b$ events

charged multiplicity, $N_{ch}$

charged multiplicity, $N_{ch}$

$m_{bias}$ events passing Level-0 $p_T$ trigger are with high $N_{ch}$
2) LHCb-light Detector Set-up

~6×5 m²

~1.4×1.2 m²

3) Trigger Tracker
Detector systems with little design changes:

VELO
- No. of stations reduced from 25 to 21
- Thickness of Si reduced from 300 to 220 µm

Tracking T1 to T3
- Straw Outer Tracker ⇒ identical to TDR T6 to T9
  \((xx-uu-vv-xx\) layers/station)
- Si Inner Tracker ⇒ see IT TDR presentation
  \((x-u-v-x\) layers/station)

RICH-2, Calorimeter system (no change)

Muon system
- M1: from 4-gap MWPC with foam plates to
  2-gap MWPC with honeycomb plates (prototypes already built)
  ⇒ Addendum to LHCC describing the RPC→MWPC change in January
Beam Pipe with Al bellows

LHC Vacuum Group

VELO tank exit window

Al prototypes (2mm) under construction at CERN

Be prototype being ordered

10 mrad section, Be-Al alloy (material being tested)

25 mrad section
To increase the performance of the Level-1 trigger:
find large impact parameter tracks (VELO) with “large” \( p_T: \mathcal{O}(1 \text{ GeV/c}) \)

- No (little) B field in VELO: easy track finding
- B field right after VELO: \( p \) measurement by extrapolating VELO tracks to TT station

1) the shielding plate is removed
   B field @ RICH-1

2) TT station with Si strip detectors
   signal fed to the Level-1 trigger a la VELO
RICH-1

- No entrance window
- Composite spherical mirrors with support outside of the acceptance
- Two-mirror optics a la RICH-2
- Photon detectors at vertical positions with Fe shielding box
  \( (B<10 \text{ Gauss for HPD's}) \)
Si sensors: 500 $\mu$m thick, strips with $\sim$240 $\mu$m pitch and connected up to 33 cm long total $\sim$3% $X_0$
Technical design of beam pipe, TT and RICH-1 will be given in the “LHCb-light” TDR to be submitted in September 2003. Trigger TDR will be submitted at the same time as the LHCb-light TDR since Level-1 is tightly coupled to the LHCb-light design. (Level-0 design has been completed and validated) Their production schedules are compatible with the 2007 LHC start-up.

Result of material optimization

\[ X_0 \] in front of RICH-2

At the time of Outer Tracker TDR
September 2001
60%

Now
39%
TT

same as the IT schedule

<table>
<thead>
<tr>
<th>Trigger</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>2003-2005</td>
<td>Construction and test of final prototypes</td>
</tr>
<tr>
<td>Sep 2004</td>
<td>Start of module production</td>
</tr>
<tr>
<td>Jan 2006</td>
<td>Start of individual commissioning</td>
</tr>
<tr>
<td>Sep 2006</td>
<td>Ready for global commissioning</td>
</tr>
<tr>
<td>Sep 2006</td>
<td>Procurement of CPUs</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>RICH-1</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feb 2004</td>
<td>Engineering design review</td>
</tr>
<tr>
<td>July 2004</td>
<td>Complete production drawings</td>
</tr>
<tr>
<td>Sep 2004</td>
<td>Place orders for superstructure and mirrors</td>
</tr>
<tr>
<td>Aug 2005</td>
<td>Begin assembly at CERN</td>
</tr>
<tr>
<td>Oct 2005</td>
<td>All mirrors produced and tested</td>
</tr>
<tr>
<td>Dec 2005</td>
<td>Begin installation in IP8</td>
</tr>
<tr>
<td>Sep 2006</td>
<td>Complete stand-alone commissioning with &gt;50% HPDs</td>
</tr>
<tr>
<td>Sep 2006</td>
<td>Ready for integrated commissioning</td>
</tr>
</tbody>
</table>
3) LHCb-light Tracking

<23> VELO track

<27> long tracks

<10> VELO + TT tracks

<10> T+TT tracks

<4> T tracks

VELO tracks
straight line
found in VELO,
starting point of long tracks

Most of physics is done
with the long tracks.

Simulation includes:
- properties of bunch collisions such as
  multiple interactions in the same collision
  interactions from the previous collision,
etc.
- complete detector response e.g.
  integration time, noise, cross talk etc.
Long tracks:

For tracks leaving at least 3 space points in VELO and 1 space point in each T station: reconstruction efficiency is 95% for $p > 10$ GeV/$c$. 

Long track efficiency = 
\[
\frac{\text{no of reconstructed long tracks}}{\text{no of tracks (VELO + T1 to T3)}},
\]

Efficiency

$p$ [GeV/$c$]
Found tracks have many clusters and most of them are the correct ones.
They have a good momentum resolution: \( \sim 4.5 \times 10^{-3} \) @ \( p = 50 \text{ GeV/c} \) and impact parameter resolution: \( \sim 50 \mu\text{m} \) @ \( p_T = 1 \text{ GeV/c} \).

Similar to VELO TDR
Ghost tracks are due to accidental combinations of clusters.

\[
\text{Ghost rate} = \frac{\text{No. of ghost long tracks}}{\text{No. of all long tracks}}
\]

For the B reconstruction, usually some \( p_T \) cuts are required (e.g. >1 GeV/c for \( B_s \to D_s \pi \)), i.e. the relevant ghost rate is small.
Due to the B field, very low momentum tracks cannot reach the T stations.

We lose tracks below 2.5 GeV/c:

- physics: kaon tag
- slow π from D* decay

RICH PID: background in the pattern recognition for long tracks

VELO+TT tracks
Reconstruction efficiency and ghost rate for the VELO-TT tracks

\[ \frac{\sigma_p}{p} = 0.2 \text{ (constant up to 5 GeV/c)} \]

Kaon ID efficiency for long tracks at low momentum increases from 50% to >80%.
K_S reconstruction
1/3 of K_S from B_d \rightarrow J/\psi K_S can be reconstructed from long tracks.
1/3 have not enough VELO hit but decay before TT → another tracking needed

T tracks
almost straight line found in T stations, starting point of TT+T tracks

T+TT tracks Efficiency of finding T+TT tracks.
In average, 4 ghost T+TT tracks per event.

Combining two oppositely charged T+TT tracks forming a vertex:

Cuts versus efficiency must be tuned depending on the B decay modes.
Electron and positron reconstruction
-recovering of bremsstrahlung photons

In the LHCb-light set-up
directions of BS photons
are known.

Energy lost by BS ($E_1$) can be
added to the electron energy.
Momentum $p$ measured by the
spectrometer = $E_2$

electron identification
efficiency = 80%
pion misidentification rate = 1%
4) Particle Identification

Compared to TDR

- Number of hit pixels reduced, due to the improved beam pipe
- Number of p.e./track is comparable
  - Aerogel 6.8 (6.6)
  - C4F10 30.3 (32.7)
  - CF4 23.2 (18.4)
- Tracks are found with real pattern recognition i.e. with ghosts

Performance will improve with further tuning
K-π separation for true pions

Average separation (in $\sigma$) as a function of momentum

Three $\sigma$ separation for $3 < p < 80$ GeV/c
Comparison with the RICH TDR

RICH TDR; perfect track finding (with real RICH pattern recognition)
Now: real track finding

The performance is already very comparable

Muon identification efficiency = 86%

Pion misidentification rate = 1%
5) M1 optimization

For $\pi^0$ reconstruction from the E-cal clusters

Original M1
four-gap MWPC with foam plates
$\sim$34% $X_0$ in average

Now reduced to
two-gap MWPC with honeycomb plates
$\sim$15% $X_0$ in average

M1 material introduce migration of $\gamma\gamma \rightarrow \gamma(e^+e^-) \rightarrow \gamma(e^+e^-)\gamma(e^+e^-)$ after the magnet
purity for $0.1 < m < 0.17 \text{ GeV}/c^2$:
0.2($\gamma\gamma$), 0.19($\gamma ee$), 0.14(eeee)  
0.21($\gamma\gamma$), 0.17($\gamma ee$), 0.14(eeee)

The $\gamma$ energy resolution is worse by $\sim15\%$ if converted, however with no major effect.
6) Improvement of the Level-1 trigger

TP low-level trigger
Level-0: high $P_T$ seeds
Level-1: tracks with large impact parameters ($d_0$)

Improved low-level trigger
Level-0: high $P_T$ seeds
Level-1: tracks with large $d_0$ and high $P_T$

Minimum Bias

\[ \sum_i \log (\frac{d}{\sigma_d}) \]

\[ \sum_i \log p_T^i \]

\[ B_d \rightarrow \pi^+ \pi^- \]

\[ B_s \rightarrow D_s K \]
Reconstruct primary vertex
Find large impact parameter tracks (>200\,\mu m)
Extrapolate them to TT and determine $p_T$
The $p_T$ resolution is sufficient to identify low $p_T$ tracks
High $p_T$ and a large impact parameter are also required in the final state reconstruction: increase the trigger efficiency for events with “reconstructable” final states.
7) Final State Reconstruction

Event generation
Detector simulation
Digitization and reconstruction
Brunel, detector-XML

Physics analysis
DaVinci

Pythia + QQ
SICB-MC, GEANT 3, detector-cdf

FORTRAN

This transition has been completed beginning of July 2002.

Data production: end of July → middle of September
3.6 M events were generated @ 7 centres of various sizes
~100k events/day is possible

- Pattern recognition done everywhere (Trigger in TP)
- Detector response are now tuned with test beam data
  wherever possible and includes all the details.
This was the first physics study with the new software
  Some problems with the data discovered...
    - several bugs in digitization and reconstruction
      e.g. detector was not as efficient as it should be
      bad vertex resolution

Bugs are fixed now:
  😊 Signal data have been reprocessed.
  😞 Quick reprocessing of the large $b\bar{b}$ sample is not possible.

What is going to be shown now
  signal study: events reconstructed with “state of the art” software
  background study: events reconstructed with imperfect software
    (~ Technical Proposal statistics)

For TDR, a new set of large statistics $b\bar{b}$ inclusive events needed
  $\rightarrow$ next data challenge in Feb-April 2003 (10 times more data)
$B_s \rightarrow D_s(\rightarrow KK\pi)\pi$ decay

four final state particles with small and large momenta

good proper-time resolution needed for the oscillation study

mass resolution
12 MeV/$c^2$

$V_z(B)$ resolution
169 $\mu$m

proper-time resolution
43 fs

(TP: 11 MeV/$c^2$, 162 $\mu$m, 43 fs with no tail)
$B_d \to \pi\pi$ decay

two large momentum particles

good $\pi/K$ separation needed

mass resolution

$18 \text{ MeV}/c^2$

proper-time resolution

$42 \text{ fs}$

Background from

$B_d \to K\pi$

$B_s \to KK$

$B_s \to K\pi$

$\Lambda_b \to p\pi$

$\sigma_{\text{mass (signal)}} = 18 \text{ MeV}/c^2$

$B \to \pi^+\pi^-$

$\sigma = 42 \text{ fs}$

(TP: $17\text{ MeV}/c^2$ and $42 \text{ fs}$)
Current status of the analysis (single pp interaction events)

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>$\varepsilon_{\text{tot}}$ (%)</th>
<th>Backg./Signal (90% CL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_d \rightarrow \pi^+\pi^-$</td>
<td>0.74</td>
<td>&lt;1.0</td>
</tr>
<tr>
<td>$B_s \rightarrow K^+K^-$</td>
<td>0.90</td>
<td>&lt;0.7</td>
</tr>
<tr>
<td>$B_s \rightarrow D_s\pi$</td>
<td>0.31</td>
<td>&lt;2.7</td>
</tr>
<tr>
<td>$B_s \rightarrow D_sK$</td>
<td>0.48</td>
<td>&lt;12</td>
</tr>
<tr>
<td>$B_s \rightarrow J/\psi(\text{ee})\phi$</td>
<td>0.34*</td>
<td>&lt;27</td>
</tr>
<tr>
<td>$B_s \rightarrow J/\psi(\mu\mu)\phi$</td>
<td>2.16</td>
<td>&lt;3.1</td>
</tr>
<tr>
<td>$B_d \rightarrow K^{*0}\gamma$</td>
<td>0.11</td>
<td>&lt;11</td>
</tr>
</tbody>
</table>

$\varepsilon_{\text{tot}} = \varepsilon_{\text{acceptance}} \times \varepsilon_{\text{reconstruction}} \times \varepsilon_{\text{trigger}}$

$\varepsilon_{\text{reconstruction}} = \varepsilon_{\text{tracks}} \times \varepsilon_{\text{physics cuts}},$  
flavour tagging not included

$\varepsilon_{\text{trigger}} = \varepsilon_{\text{Level-0}} \times \varepsilon_{\text{Level-1}}$

* Reconstruction efficiency of $B_s \rightarrow J/\psi(\text{ee})\phi$ is a half of $B_s \rightarrow J/\psi(\mu\mu)\phi$.
Trigger needs further optimization.
A direct comparison to TP performance is difficult...
- physics cuts are not optimized yet (requires new $b\bar{b}$ inclusive data)

TP $\varepsilon_{\text{tot}}$ with Level-2, no flavour tag \hspace{1cm} ($\varepsilon_{\text{tot}}$ now without Level-2)

<table>
<thead>
<tr>
<th></th>
<th>$\pi^+\pi^-$</th>
<th>$D_s\pi$</th>
<th>$D_sK$</th>
<th>$D_sK^*$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\varepsilon$</td>
<td>0.55% (0.74%)</td>
<td>0.55% (0.31%)</td>
<td>0.49% (0.48%)</td>
<td></td>
</tr>
</tbody>
</table>

$J/\psi(\mu\mu)\phi$ 2.21\% (2.16\%) $K^*\gamma$ 0.18\% (0.11\%)

(TP time $\varepsilon_{\text{Level-2 trigger}} = 0.8\sim0.9$)

With “LHCb-light” detector

Track reconstruction efficiency is good

PID efficiency $\}$ are similar to TP
Track quality

Trigger efficiency is good.

|$\downarrow$

A TP level physics performance can be achieved after physics cuts are optimized.
8) Plan for the “LHCb-Light” TDR

Final detector set-up (including M1 decision) ✓
Development of Brunel software
   completed by end of November 2002

Preproduction
   starts 17 December 2002

Production
   starts 5 February 2003

TDR first complete draft
   by 27 June 2003

TDR sent for printing
   on 9 September 2003
9) Conclusions

- Re-optimization work has successfully reduced the amount of material to 39% of \( X_0 \).

- New tracking system based on a reduced number of stations can achieve efficient track finding, excellent momentum and impact parameter resolution, and low ghost rate.

- RICH particle identification is not compromised by the new tracking system and the reduced material enhances the detection capability for electrons.

- Introduction of B field between VELO and Si TT station enhances the efficiency and robustness of the Level-1 trigger.

- Preliminary physics study shows that we can achieve final state reconstruction efficiencies similar to those presented in the Technical Proposal, although the current simulation program includes the realistic aspects of the experiment.
And we are working hard towards the “LHCb-light” TDR to be submitted in September 2003.