LHCb: Reoptimized Detector & Tracking Performance

Gerhard Raven
NIKHEF and VU, Amsterdam
Representing
the LHCb collaboration

Beauty 2003,
Carnegie Mellon University,
Oct 14-18,
Pittsburgh, PA, USA
The LHCb collaboration has completed all the “detector” TDR’s

- Feb 1996: *LHCb* Letter of Intent
- Sep 1998: Technical Proposal approved
- 2000—2002: Technical Design Reports of all detector subsystems
- Sep 2003: LHCb re-optimization & Trigger TDRs
- Remaining: Computing TDR (next year)
Direct Measurement of angles:
- $\sigma(\sin(2\beta)) \approx 0.03$ from $J/\psi K_s$ in B factories
- Other angles not precisely known

Knowledge of the sides of unitary triangle:
(Dominated by theoretical uncertainties)
- $\sigma(|V_{cb}|) \approx$ few % error
- $\sigma(|V_{ub}|) \approx$ 5-10 % error
- $\sigma(|V_{td}|/|V_{ts}|) \approx$ 5-10% error
  (assuming $\Delta m_s$ observed)

In case new physics is present in mixing, independent measurement of $\gamma$ can reveal it…

See Ulrich Uwer’s talk on Saturday for 3 separate examples of the determination of $\gamma$ at LHCb
(2 of which require $B_s$ mesons…)
LHCb: Forward Spectrometer with:
- Efficient trigger and selection of many B meson decay final states
- Good tracking and Particle ID performance
- Excellent momentum and vertex resolution
- Adequate flavour tagging

Large $b\bar{b}$ production cross section:
$10^{12} b\bar{b}$/year at $2 \times 10^{32}$ cm$^{-2}$s$^{-1}$

Triggering is an issue

All $b$ hadrons are produced:
- $B_u$ (40%), $B_d$ (40%), $B_s$ (10%),
- $B_c$ and $b$-baryons (10%)

Many tracks available for primary vertex

Many particles not associated to $b$ hadrons

$b$ hadrons are not coherent: mixing dilutes tagging
Evolution since Technical Proposal

- Reduced material
- Improved level-1 trigger

Single arm forward spectrometer
15 mrad < \theta < 300 mrad (1.8 < \eta < 4.9)

\( X_0 : 40\% \rightarrow 12\% \)
Monte Carlo Generation

- **pp interactions**
  - Minimum bias events from PYTHIA 6.2
    - Hard QCD processes, single and double diffraction
    - Multiple parton interactions tuned to reproduced track multiplicities observed at SPS and Tevatron energies
  - bb events
    - Extracted from minimum bias sample

- **bunch crossings in LHCb**
  - Size of luminous region
  - Simultaneous pp interactions ("pileup")
    - Number of visible interactions \( n \) (in events with at least one) distributed according to
    \[ L = 2 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}, \langle \nu \rangle = 30 \text{ MHz} \]
    
    \[ \langle n \rangle_{\text{bb \ event}} = 1.42 \]

\[ \sigma_{\text{total}} = 100 \text{ mb} \]
\[ \sigma_{\text{visible}} = 65 \text{ mb} \]
\[ \sigma_{\text{bb}} / \sigma_{\text{visible}} = 0.8\% \]
\[ \sigma_{x} = \sigma_{y} = 70 \mu\text{m}, \sigma_{z} = 5 \text{ cm} \]
Simulation and Reconstruction

- Full GEANT 3.2 simulation
  - Complete description from TDRs
- Detector response
  - Based on test-beam data (resolution, efficiency, noise, cross-talk)
  - Spill-over effects included (25 ns bunch spacing)
- Trigger simulation
  - Thresholds tuned to get maximal signal efficiencies at limited output rates of 1 MHz (L0) and 40 kHz (L1)
  - No full HLT simulation (yet)
- Offline reconstruction
  - Full pattern recognition (track finding, RICH reconstr. …)

No true MC info used anywhere!
Simulation and Reconstruction

Simulated samples:
• Dedicated signal samples
• Background samples: 10 M incl. bb events ⇒ 4 min
  30 M min. bias events
Tracking Detectors: **VELO**

- 21 Stations, back-to-back
- R and $\phi$ sensors
- 220 $\mu$m thin silicon
- 180K channels

Pile-Up Stations

Interaction Region $\sigma=5.3$ cm

Cross section at $y=0$: 390 mrad, 60 mrad, 15 mrad

Not required for LHCb acceptance coverage
Tracking Detectors:

- Sensors are located in 2ndary vacuum
- Separated from beams by RF foil (300 µm Al+3% Mg)
- Retractable during injection
Tracking Detectors: VELO

VELO is mounted on movable x-y tables to stay (actively) centered around the beam.
Exit window of VELO is also entry window of RICH-1
Four Layers of Si strip detectors
two stations: Vertical, +5°; -5°, Vertical
Total area of Si: 8.3 m²

Magnet field (0.15 Tm) between VELO + TT allows initial momentum estimate of high IP tracks in Level-1 trigger
→ Field constraint by RICH1 shielding
→ Requires all silicon detector…
Tracking Detectors: Trigger Tracker

198 µm strip pitch, up to 30 cm long strips → 410 µm thick
180K readout channels
Magnet

- dipole
- warm Al conductor
- 4 Tm integrated field
- 4.2 MW
- 1450 t yoke

- All components delivered
- Underground assembly ongoing
Tracking Detectors: T stations

- Split into two systems
  - Inner and Outer Trackers

- particle fluences higher in equatorial plane (bending plane of magnet)
  - extend horizontal coverage of Inner Tracker

- Inner Tracker area
  - covers only 1.3% of sensitive overall tracker area
  - corresponds to 20% of all tracks within LHCb acceptance
  - Instrumented with silicon strip detectors

- Outer Tracker area
  - Large area
  - Instrumented with strawtube chambers

\[ \sim 6 \times 5 \text{ m}^2 \]
Tracking Detectors: Outer Tracker

- 3 stations with 4 double layers
- 5mm straw tubes
- 50k readout ch.
Tracking Detectors: Inner Tracker

- 3 stations with 4 layers each
- 320µm thin silicon
- 198µm readout pitch
- 130k readout ch.
Track finding strategy

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

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

20–50 hits assigned to a long track:
98.7% correctly assigned

Eff = 94%
(p > 10 GeV)

Ghost rate = 3%
(for $p_T > 0.5$ GeV)

Ghosts:
Negligible effect on
B decay reconstruction

On average:
26 long tracks
11 upstream tracks
4 downstream tracks
5 T tracks
26 VELO tracks

Efficiency vs $p$:

Ghost rate vs $p_T$:

[Graphs showing efficiency and ghost rate as functions of $p$ and $p_T$]
$K_S \rightarrow \pi^+\pi^-$ reconstruction

- $K_S$ from $B^0 \rightarrow J/\psi$ $K_S$
  - 25% decay after TT
    - Not reconstructed
  - 50% decay outside VELO but before TT
    - Use pairs of downstream tracks
  - 25% decay inside VELO
    - Use long and upstream tracks

Combinatorial background removed when $K_S$ combined with $J/\psi$ into a $B^0$ meson

Entries vs. Invariant mass (MeV/$c^2$)

- Downstream downstream $\varepsilon = 54\%$ $\sigma = 7$ MeV
- Long downstream $\varepsilon = 75\%$ $\sigma = 4$ MeV
- Long upstream $\varepsilon = 61\%$ $\sigma = 12$ MeV
Primary Vertex Reconstruction

- $b \bar{b}$ production vertex found in 98% of $b \bar{b}$ events
- Multiple primary vertices
  ⇒ use back-pointing of reconstructed B to find correct one

**Primary Vertex $x,y$**
- Mean $= 0.4 \pm 0.1 \, \mu m$
- $\sigma_1 = 7.8 \pm 0.2 \, \mu m$
- $\sigma_2 = 18 \, \mu m$ (26.5%)
- $\sigma$(core) $\sim 8 \, \mu m$

**Primary Vertex $z$**
- Mean $= 8.3 \pm 0.8 \, \mu m$
- $\sigma_1 = 43.9 \pm 1.6 \, \mu m$
- $\sigma_2 = 124 \, \mu m$ (21.8%)
- $\sigma$(core) $\sim 45 \, \mu m$
**Track Resolution**

**Impact parameter resolution**

\[ \sigma_{IP} = 14\mu + 35\mu/p_T \]

**Momentum resolution**

\[ \delta p/p = 0.35\% - 0.55\% \]
Mass Resolution

Need excellent momentum resolution to reject backgrounds by cutting on resonant masses, eg. $B_{(s)}$ mass, $D_s$ mass, $J/\psi$ mass

Mass of $D_s \rightarrow K^+ K^- \pi^-$

$m_{D_s} = 1.97 \text{ GeV}/c^2$

$\sigma_{D_s} = 5.5 \text{ MeV}/c^2$

Mass of $B_s \rightarrow D_s^- (K K \pi) \pi^+$

$\sigma = 14 \text{ MeV}/c^2$

$\sigma_{core} = 12.6 \pm 0.6 \text{ MeV}$
Proper time resolution

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

\[ \sigma(\Delta m_s) = 0.011 \text{ ps}^{-1} \]

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

More physics examples: Ulrich Uwer on Saturday
Example:

B_s \rightarrow D_s K decays

BR(B_s \rightarrow D_s \pi^+)/BR(B_s \rightarrow D_s \rightarrow K^{+}) \sim 12

See next talk by Marco Adinolfi on the LHCb RICH
Trigger Strategy

**Level-0:**
- $p_T$ of $\mu$, $e$, $h$, $\gamma$
- 40 MHz
- Calorimeter
- Muon system
- Pile-up system
- 1 MHz

**Level-1:**
- Impact parameter
- Rough $p_T \sim 20\%$
- 40 kHz
- Vertex Locator
- Trigger Tracker
- Level 0 objects

**HLT:**
- Final state reconstruction
- Full detector information
- 200 Hz output

See talk by Olivier Callot on Friday on implementation and performance
Calorimeters and Muon System

Ecal: 100% constructed

Hcal: 30% constructed

See talk by Frédéric Machefert on LHCb Calorimeters & Muon system (in ~22 minutes)
Conclusions

- LHC offers great potential for B physics from “day 1” LHC luminosity
- LHCb experiment has been reoptimized:
  - Less material in tracking volume
  - Improved Level1 trigger
- Realistic trigger simulation and full pattern recognition in place
- Tracking performance meets the requirements set by physics goals of the experiment
- LHC startup is now only 3.5 years away
  - Construction of the experiment is well underway
Backup
Figure 1.2: Material seen by a neutral particle from the nominal position of the primary vertex as a function of the pseudo-rapidity at three different z positions, averaged over the azimuthal angle.
Systematic Effects

Possible sources of systematic uncertainty in CP measurement:

- Asymmetry in $b\bar{b}$ production rate
- Charge dependent detector efficiencies…
  - can bias tagging efficiencies
  - can fake CP asymmetries
- CP asymmetries in background process

Experimental handles:

- Use of control samples:
  - Calibrate $b\bar{b}$ production rate
  - Determine tagging dilution from the data:
    - e.g. $B_s \rightarrow D_s \pi$ for $B_s \rightarrow D_s K$, $B \rightarrow K\pi$ for $B \rightarrow \pi\pi$, $B \rightarrow J/\psi K^*$ for $B \rightarrow J/\psi K_s$, etc
- Reversible $B$ field in alternate runs
- Charge dependent efficiencies cancel in most $B/\bar{B}$ asymmetries
- Study CP asymmetry of backgrounds in $B$ mass “sidebands”
- Perform simultaneous fits for specific background signals:
  - e.g. $B_s \rightarrow D_s \pi$ in $B_s \rightarrow D_s K$, $B_s \rightarrow K\pi$ & $B_s \rightarrow K K$, …