Run I Legacy Performance of LHCb
from Principle to Real Life

Giacomo Graziani
(INFN, Firenze)
on behalf of the LHCb Collaboration

Rencontres du Vietnam
Physics at LHC and beyond
August 11, 2014
The Challenge of LHCb

LHCb is the experiment devoted to heavy flavours at the LHC.

✔ Exploiting large $b\bar{b}$ production at high $|\text{rapidity}|$

✗ But need to identify heavy flavour decays from huge hadronic background

✗ High particle density in this rapidity region, experimental challenge

⇒ Forward detector with key features:

$(2 < \eta < 5)$

- Daring vertex detector design
- Excellent particle ID: $\pi/K$ separation in 1-100 GeV/c range
- Fast, efficient and flexible high-bandwidth Trigger System

- Operating at lower pileup/luminosity than ATLAS/CMS
The Detector: Tracking

**Vertex Locator**

Si μ-strips sensors, orthogonal to beam, rφ geometry, movable device from 30 to 8 mm from beam!

**Tracking Stations**

Si detector for upstream and inner parts (ST), straw tubes for outer part (OT)

**Magnet**

Warm dipole, 4 Tm
Polarity regularly changed (~ 2 weeks)
The Detector: Particle ID

**RICHs**
2 detectors using 3 radiators for π/K separation in wide momentum range (1-100 GeV/c). Readout by custom HPDs.

**Calorimeter System**
Scintillator Pad Detector, PreShower (Pb/scint. pads), ECAL (Pb/scint. tiles), HCAL (Fe/scint. tiles).

**Muon System**
5 stations, 1 before CALOs MWPC, except GEMs for the inner part of M1.
An evolving Physics case

Focus in 1998 (Technical Proposal)
- Test validity of CKM paradigm using “golden” CPV processes

Today
- After the successful B-factories and Tevatron programs, demonstrating the SM description of CPV at tree level, focus moved to loop processes sensitive to New Physics at higher scales
- Broaden physics program to include CPV in charm, b-baryons...
- ...and a rich program in flavour spectroscopy (exotica, double heavy states, ...) and more (EW physics, proton-lead collisions...)

⇒ evolution of trigger design and operation strategy toward a more general-purpose forward detector
LHCb Operation

Principle

- 25 ns bunch spacing, 2808 bunches, 14 TeV
- Fight pile-up events: work at \( \mu = 0.7 \) visible interactions/crossing (maximize number of events with single interaction)
- Luminosity = \( 2 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1} \), 2 fb\(^{-1}\) per year

Real Life

- 50 ns bunch spacing, 7/8 TeV < 1300 bunches
- Pile-up up to \( \mu = 3 \)
- Learn by experience:
  - verify detector & physics performance under these harsh conditions
  - exploit trigger flexibility to adapt its configuration
- Push luminosity for rare decays
  \( \Rightarrow \) 2012 “compromise” working point
  \( \mathcal{L} = 4 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1} \) \( \mu = 2.1 \)
Luminosity levelling

- Luminosity adjusted dynamically to required level during fills by beam transverse displacement
- Great interplay between machine and experiment!
- Maximum integrated lumi., stable trigger configuration

More on Run I Operation ⇒ talk by C.Gaspar later today
Integrated Luminosity

After data quality requirements:

- 1.0 fb$^{-1}$ in 2011@7 TeV
- 2.0 fb$^{-1}$ in 2012@8 TeV (nominal lumi/year of TDR!)
- +1.6 nb$^{-1}$ proton-Pb@$\sqrt{s}=5$ TeV
The LHCb Trigger

Principle (trigger TDR 2003)

Real Life

Pile-up veto removed from L0 (replaced by global cut on track multiplicity)

Maximize output rate for wider physics program (charm physics, hadron spectroscopy, data mining)

L1 removed in 2005

⇒ full 1 MHz software trigger with 2 kHz output! big gain in flexibility

Further development for Run II, expect to reach 12.5 kHz!
⇒ talk by K.Hennessy on Friday
L0 Trigger

Principle (trigger TDR 2003)

<table>
<thead>
<tr>
<th>Decay Channel</th>
<th>( \epsilon_{L0}(%) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( B^+ \rightarrow J/\psi(\mu^+\mu^-)K^+ )</td>
<td>90.3 ± 0.4</td>
</tr>
<tr>
<td>( B^0 \rightarrow K^+\pi^- )</td>
<td>54.1 ± 0.8</td>
</tr>
</tbody>
</table>

trigger TDR CERN/LHCC 2003-031

Real Life

HLT1: fast track/vertex reconstruction, selects tracks from their \( p_T \)/displacement, and high-mass dimuons

\[ J/\psi K^+ \]

\[ J/\psi K^- \]

HLT2: full reconstruction and inclusive/exclusive selections, also using MVA algorithms

Performance/flexibility well beyond original design
**Principle**

**Daring design:**
- Detector halves moving from 30 to 8 mm from axis when stable beam declared

**Concerns:**
- Safety!
- Radiation damage fluence up to $5 \times 10^{13} \text{ n}_{eq} / (\text{cm}^2 \text{ fb}^{-1})$
  $\Rightarrow$ complete spare detector built

**Real Life**
- Beam orbit proved to be very stable
- Effect of rad. damage well controlled, effects on performance acceptable
- Detector replacement not foreseen during Run II
VELO Spare detector

On display at LHCb site (Point 8), main LHCb tourist attraction!
VELO Performances

**Principle**
- Simplified TDR simulations (2003): aim at proper time resolution ~ 40 fs for $B_s \to J/\psi \phi$

**Real Life**
- Detector response in good agreement with simulations
- Achieved average proper time resolution 45 fs

![Graph showing Primary Vertex Resolution](image1)

![Graph showing Impact Parameter Resolution](image2)

![Graph showing Proper Time Resolution for $B_s \to J/\psi \phi$](image3)

*arXiv:1405.7808*
Tracking Performances

- Main tracker performances also in line with expectations
- Aging effects in Outer Tracker: understood and fixed
- Track finding efficiency only slightly reduced in crowded events
- Momentum resolution 0.4 – 0.6% for \( p < 100 \) GeV/c
- Best mass resolution for quarkonia at LHC!

\[
\sigma(M_{J/\psi}) = 13 \text{ MeV/c}^2
\]
\[
\sigma(M_{\Upsilon(1S)}) = 43 \text{ MeV/c}^2
\]
RICH Performances

- RICH1 covering low (2-60 GeV/c) p region, using Aerogel and C$_4$F$_{10}$ radiators
- RICH2 covers higher momenta with CF$_4$ radiator

Detector suffering most from higher track multiplicity

Aerogel performance slightly worse than expected
Though, overall performance close to expectations
Calorimeter Performances

- Calorimeter system identifies electrons/photons/$\pi^0$/neutral hadrons combining information from:
  - Scintillating pad detector
  - Preshower
  - ECAL
  - HCAL
- Achieved expected resolution of $<9$ MeV/$c^2$ on $\pi^0$ mass

Example of radiative decay: $B^0 \rightarrow K^*\gamma$
$\sigma=93$ MeV/$c^2$, dominated by ECAL

- Electron identification performance in line with expectations: 5.5% misID rate for 90% efficiency
Detector efficiency beyond expectations

Muon identification performances agree well with expectations: misID rate for hadrons < 0.6% for efficiency = 93%

required level = 99%
Physics Performances

- Benchmark numbers on $B_s$ oscillations (statistical uncertainties with 1 fb$^{-1}$):
  
  **Principle (TDR 2003)**
  \[
  \sigma(\Delta m_s) = 0.015 \text{ ps}^{-1} \\
  \sigma(\Delta \Gamma_s) = 0.017 \text{ ps}^{-1} \\
  \sigma(\phi_s) = 0.09 \text{ rad}
  \]
  
  **Real Life (1 fb$^{-1}$ results)**
  
  \[
  \sigma(\Delta m_s) = 0.023 \text{ ps}^{-1} \\
  \sigma(\Delta \Gamma_s) = 0.011 \text{ ps}^{-1} \\
  \sigma(\phi_s) = 0.07 \text{ rad}
  \]

Measurements still limited by statistics!
**Physics Performances**

- Benchmark numbers on $B_s$ oscillations (statistical uncertainties with 1 fb$^{-1}$):
  - Principle *(TDR 2003)*
    - $\sigma(\Delta m_s) = 0.015$ ps$^{-1}$
    - $\sigma(\Delta \Gamma_s) = 0.017$ ps$^{-1}$
    - $\sigma(\phi_s) = 0.09$ rad
  - Real Life *(1 fb$^{-1}$ results)*
    - $\sigma(\Delta m_s) = 0.023$ ps$^{-1}$
    - $\sigma(\Delta \Gamma_s) = 0.011$ ps$^{-1}$
    - $\sigma(\phi_s) = 0.07$ rad

  Measurements still limited by statistics!

Most cited LHCb physics results today:
1. $B_s \rightarrow \mu\mu$
2. CPV in $D^0 \rightarrow hh$ decays
3. $b\bar{b}$ production
4. $J/\psi$ production
5. $\Phi_s$ measurement
6. $b$ fragmentation fractions
7. $X(3872)$ quantum numbers

---

<table>
<thead>
<tr>
<th>Decay Modes</th>
<th>Visible Br. fraction</th>
<th>Offline Reconstr.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0_d \rightarrow \pi^+\pi^- + \text{tag}$</td>
<td>$0.7 \times 10^{-5}$</td>
<td>6.9 k</td>
</tr>
<tr>
<td>$B^0_d \rightarrow K^+\pi^-$</td>
<td>$1.5 \times 10^{-5}$</td>
<td>33 k</td>
</tr>
<tr>
<td>$B^0_d \rightarrow \rho^+\pi^- + \text{tag}$</td>
<td>$1.8 \times 10^{-5}$</td>
<td>551</td>
</tr>
<tr>
<td>$B^0_d \rightarrow J/\psi K_S + \text{tag}$</td>
<td>$3.6 \times 10^{-5}$</td>
<td>56 k</td>
</tr>
<tr>
<td>$B^0_d \rightarrow D^0 K^{*0}$</td>
<td>$3.3 \times 10^{-7}$</td>
<td>337</td>
</tr>
<tr>
<td>$B^0_d \rightarrow K^{*0}\gamma$</td>
<td>$3.2 \times 10^{-5}$</td>
<td>26 k</td>
</tr>
<tr>
<td>$B^0_s \rightarrow D^-\pi^+ + \text{tag}$</td>
<td>$1.2 \times 10^{-4}$</td>
<td>35 k</td>
</tr>
<tr>
<td>$B^0_s \rightarrow D^-K^+ + \text{tag}$</td>
<td>$8.1 \times 10^{-6}$</td>
<td>2.1 k</td>
</tr>
<tr>
<td>$B^0_s \rightarrow J/\psi \phi + \text{tag}$</td>
<td>$5.4 \times 10^{-5}$</td>
<td>44 k</td>
</tr>
</tbody>
</table>

"golden" channels mentioned in TP (1998)
LHCb detector looking forward to be able to acquire much more data:

- Run II plans
  ⇒ talk by K.Hennessy on Friday

- Upgrade plans, aiming at increase luminosity by up to 5x from 2019 and collect >50 fb$^{-1}$
  ⇒ talk by O.Steinkamp on Friday

• Reality sometimes beyond (realistic) dreams!