Motivation

LHCb is a high precision experiment devoted to the search for New Physics (NP) beyond the Standard Model (SM) by
- studying CP violation and rare decays in the b and c-quark sectors
- searching for deviations from the SM due to virtual contributions of new heavy particles in loop diagrams
- being sensitive to new particles above the TeV scale not accessible to direct searches

Past and running experiments have shown that:
- flavour changing processes are consistent with the CKM mechanism
- large sources of flavour symmetry breaking are excluded at the TeV scale
- the flavour structure of the NP, if it exists, would be very peculiar at the TeV scale (MFV)

However:
- measurable deviations from the standard model are still expected, but should be small
- need to go to very high precision measurements to probe the most clean observables

→ LHCb upgrade essential to increase statistical precision significantly
Few highlights of LHCb results

\[ \Phi_s = 0.01 \pm 0.07 (\text{stat}) \pm 0.01 (\text{syst}) \]

\[ B^0 \rightarrow K^{*0} \mu^+ \mu^- \]

\[ q_0^2 = 4.9 \pm 0.9 \text{ GeV}^2/c^4 \]

\[ BR(B_S^0 \rightarrow \mu^+ \mu^-) = (2.9^{+1.1}_{-1.0} (\text{stat})^{+0.3}_{-0.1} (\text{syst})) \times 10^{-9} \]
Example of impact on Super Symmetric Models

Combining CMS & LHCb

\[ BR(B^0 \rightarrow \mu^+ \mu^-) = (3.6^{+1.6}_{-1.4}) \times 10^{-10} \]

\[ BR(B_s^0 \rightarrow \mu^+ \mu^-) = (2.9 \pm 0.7) \times 10^{-9} \]

D. Straub, arXiv:1205.6094
Andreas Schopper
6 June 2014 LHCP New York

LHCb upgrade $\geq 50 \text{ fb}^{-1}$:
- increase precision on quark flavour physics observables
- aim at experimental sensitivities comparable to theoretical uncertainties
- reinforce LHCb as a general purpose forward detector

LHCb up to 2018 $\geq 8 \text{ fb}^{-1}$:
- find or rule-out large sources of flavour symmetry breaking at the TeV scale

**Expected evolution of luminosity in LHCb**

<table>
<thead>
<tr>
<th>Year</th>
<th>Bunch Spacing</th>
<th>$E_{cm}$</th>
<th># of Bunch Crossings</th>
<th>$\mathcal{L}(\text{cm}^2\text{s}^{-1})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>50 ns</td>
<td>7 TeV</td>
<td>up to 1318</td>
<td>$4 \cdot 10^{32}$</td>
</tr>
<tr>
<td>2011</td>
<td>50 ns</td>
<td>8 TeV</td>
<td>up to 1318</td>
<td>$4 \cdot 10^{32}$</td>
</tr>
<tr>
<td>2012</td>
<td>25 ns</td>
<td>7 TeV</td>
<td>up to 1318</td>
<td>$4 \cdot 10^{32}$</td>
</tr>
<tr>
<td>2013</td>
<td>25 ns</td>
<td>8 TeV</td>
<td>up to 1318</td>
<td>$4 \cdot 10^{32}$</td>
</tr>
<tr>
<td>2014</td>
<td>25 ns</td>
<td>7 TeV</td>
<td>up to 1318</td>
<td>$4 \cdot 10^{32}$</td>
</tr>
<tr>
<td>2015</td>
<td>25 ns</td>
<td>8 TeV</td>
<td>up to 1318</td>
<td>$4 \cdot 10^{32}$</td>
</tr>
<tr>
<td>2016</td>
<td>25 ns</td>
<td>7 TeV</td>
<td>up to 1318</td>
<td>$4 \cdot 10^{32}$</td>
</tr>
<tr>
<td>2017</td>
<td>25 ns</td>
<td>8 TeV</td>
<td>up to 1318</td>
<td>$4 \cdot 10^{32}$</td>
</tr>
<tr>
<td>2018</td>
<td>25 ns</td>
<td>7 TeV</td>
<td>up to 1318</td>
<td>$4 \cdot 10^{32}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8 TeV</td>
<td>up to 1318</td>
<td>$4 \cdot 10^{32}$</td>
</tr>
</tbody>
</table>

LHCb up to LS2

Run 1

Run 2

Run 3

R4

LHCb upgrade

LS1

LS2

LS3

$> 8 \text{ fb}^{-1}$:
- find or rule-out large sources of flavour symmetry breaking at the TeV scale
### LHCb statistical sensitivity to flavour observables

Expected statistical uncertainties on a few selected physics channels before and after the upgrade, compared to theory

<table>
<thead>
<tr>
<th>Integrated lumi</th>
<th>LHCb up to LS2</th>
<th>LHCb upgrade</th>
<th>Theory</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Run 1</td>
<td>Run 2</td>
<td>Run 3</td>
</tr>
<tr>
<td>$Br(B_d \rightarrow \mu \mu)$</td>
<td>$Br(B_s \rightarrow \mu \mu)$</td>
<td>-</td>
<td>110 %</td>
</tr>
<tr>
<td>$q_0^2 A_{FB}(B_d \rightarrow K^{*0} \mu \mu)$</td>
<td>10 %</td>
<td>5 %</td>
<td>2.8 %</td>
</tr>
<tr>
<td>$\phi_s(B_s \rightarrow J/\psi \phi, B_s \rightarrow J/\psi \pi \pi)$</td>
<td>0.05</td>
<td>0.025</td>
<td>0.013</td>
</tr>
<tr>
<td>$\phi_s(B_s \rightarrow \phi \phi)$</td>
<td>0.18</td>
<td>0.12</td>
<td>0.04</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>7°</td>
<td>4°</td>
<td>1.7°</td>
</tr>
<tr>
<td>$A_T(D^0 \rightarrow KK)$</td>
<td>$3.4 \times 10^{-4}$</td>
<td>$2.2 \times 10^{-4}$</td>
<td>$0.9 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

From “Heavy Flavour Physics in the HL-LHC era” document prepared for the Aix-les-Bains ECFA Workshop – Oct 2013
How to increase LHCb statistics significantly

LHCb upgrade
- increase luminosity to a levelled 1-2 \( \cdot \) \( 10^{33} \) cm\(^{-2}\)s\(^{-1} \), pile-up~5
- run fully flexible & efficient software trigger up to 40 MHz
- record ~20-100 kHz

LHCb up to LS2
- running at levelled luminosity of ~ 4 \( \cdot \) \( 10^{32} \) cm\(^{-2}\)s\(^{-1} \), pile-up~1
- first level hardware trigger running at ~1 MHz
- record ~3-5 kHz

2012 running conditions

LHCb upgrade
- LHCb 2012
- CMS
- ATLAS
- Luminosity potential exhausted
- Beams head-on
- LHC Fill 2651

\( \ll 1-2 \cdot 10^{33} \) cm\(^{-2}\)s\(^{-1} \)

\( \ll \sim 4 \cdot 10^{32} \) cm\(^{-2}\)s\(^{-1} \)

LHCb 2012

1 MHz limitation

LHCb upgrade
run an efficient and selective software trigger with access to the full detector information at every 25 ns bunch crossing

→ increase luminosity and signal yields

**Trigger upgrade**

30 MHz

inelastic collision rate

**Full Software Trigger**

LLT (optional)

\( p_T \) of \( h, \mu, e, \gamma \)

(15 to) 30 MHz

Full track reconstruction

(1 to) 2 MHz

Track fit

RICH particle ID

Inclusive and exclusive selections

to storage

20 to 100 kHz

**effect on luminosity and signal yields**

![Graph showing effect on luminosity and signal yields](image)
40 MHz architecture overview

- **PCle40 board**
- **Event Builder PCs (& software LLT)**
- **Front-end electronics**
- **individual sub-systems**
- **incl. Zero-Suppression**
- **40 MHz**
- **40 MHz architecture overview**
- **Event Builder network**
- **HLT Farm**
- **20 KHz**
- **optical link via GBT**
- **~300m**
- **PC servers with PCle40 R/O**
- **LLT and Event Building**
- **on surface**
- **pure software trigger**

### Table: Event Rates and Bandwidth

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Event-size [kB]</th>
<th>Rate [kHz]</th>
<th>Bandwidth [Gb/s]</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALICE</td>
<td>20 000</td>
<td>50</td>
<td>8 000</td>
<td>2019</td>
</tr>
<tr>
<td>ATLAS</td>
<td>4 000</td>
<td>200</td>
<td>6 400</td>
<td>2022</td>
</tr>
<tr>
<td>CMS</td>
<td>4 000</td>
<td>1000</td>
<td>32 000</td>
<td>2022</td>
</tr>
<tr>
<td>LHCb</td>
<td>100</td>
<td>40 000</td>
<td>32 000</td>
<td>2019</td>
</tr>
</tbody>
</table>

[status: ECFA-Workshop 10/2013]
Detector upgrade to 40 MHz readout

- upgrade ALL sub-systems to 40 MHz Front-End (FE) electronics
- replace complete sub-systems with embedded FE electronics
- adapt sub-systems to increased occupancies due to higher luminosity
- keep excellent performance of sub-systems with 5 times higher luminosity and 40 MHz R/O

Diagram:
- Vertex Locator (VELO)
- RICH Detectors
- Muon System
- Tracking System
- Calorimeters
**Vertex reconstruction with VELO**

From $B_s \rightarrow D_s \pi$

$\sim 45$ fs time resolution

**Resolution of $IP_x$ vs $1/p_T$**

2012 Data

2012 Simulation

Current detector

Microstrip sensors ($R, \Phi$)

Movables halves $\rightarrow 5.5$ mm from beam
Upgrade challenge:

✓ withstand increased radiation
  (highly non-uniform radiation of up to $8 \cdot 10^{15}$ n$_{eq}$/cm$^2$ for 50 fb$^{-1}$)
✓ handle high data volume
✓ keep (improve) current performance
  ➢ lower materiel budget
  ➢ enlarge acceptance

Technical choice:

✓ 55x55 $\mu$m$^2$ pixel sensors with micro channel CO$_2$ cooling
✓ 40 MHz VELOPIX (evolution of TIMEPIX 3, Medipix)
  ➢ 130 nm technology to sustain ~400 M仁 in 10 years
  ➢ VELOPIX hit-rate = ~8 x TIMEPIX 3 rate
✓ replace RF-foil between detector and beam vacuum
  ➢ reduce thickness from 300 $\mu$m → ≤ 250 $\mu$m
✓ move closer to the beam
  ➢ reduce inner aperture from 5.5 mm → 3.5 mm
Andreas Schopper

VELO upgrade

Pixel detector with micro channel cooling

Micro channels
200 μm x 120 μm

Si cooling substrate ~400 μm

Micro channel cooling substrate

Sensors (front, back, bonds)

RF-foil

tracks/chip/event at \( L = 2 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1} \)

Prototype pixel sensor

1.7 1.3 0.8

8.5 3.0 1.1

8.5 1.7

3.0 1.3

1.1 0.8

~1m
3D Impact-Parameter resolution at $L = 2 \cdot 10^{33} \text{ cm}^{-2}\text{s}^{-1}$

LHCb simulation

- current
- upgrade

note: full GEANT Monte Carlo with standard LHCb simulation framework
Particle Identification with RICH

Efficient particle identification of $\pi$, $K$, $p$ essential for selecting rare beauty and charm decays

Particle identification of $2\,\pi$

$BR(B \to \pi^+\pi^-) = 5 \times 10^{-6}$!
Particles traversing radiator produce Cherenkov light rings on an array of HPDs located outside the acceptance.
Luminosity of $2 \cdot 10^{33} \text{ cm}^{-2}\text{s}^{-1}$ → adapt to high occupancies

- aerogel radiator removed
- modify optics of RICH1 to spread out Cherenkov rings
  (optimise gas enclosure without modifying B-shield)

40 MHz readout → replace HPDs due to embedded FE

- 64 ch. multi-anode PMTs (baseline)
- 40 MHz Front-End: CLARO chip (or MAROC)
**RICH upgrade**

**RICH Kaon ID RICH1-Optics-Comparison**

### Current RICH1
- $2 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$
- $10 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$
- $20 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$

### RICH1 upgrade
- $20 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$

**note:**
- full GEANT MC with standard LHCb simulation framework

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**Pion misidentification efficiency [%]**

**Kaon identification efficiency [%]**
excellent mass resolution
very low background, comparable to $e^+e^-$ machines
world’s best mass measurements

$\sigma = 7 \text{ MeV/c}^2$

- TT silicon
- IT silicon
- OT straw tubes

– TT silicon
– IT silicon
– OT straw tubes
Andreas Schopper
6 June 2014 LHCP New York

**TT upgrade: Upstream Tracker (UT)**

Adapt segmentation to varying occupancies (out → in-side):
- 98 → 49 mm long strips
- 190 → 95 μm pitch
- p⁺-in-n → n⁺-in-p

Silicon strip detector

Outer, middle, inner

Staves a la ATLAS-LBL

40MHz silicon strip
R/O → SALT chip
T-stations upgrade: Fibre Tracker (FT)

scintillating-fibre mat (5-6 layers)

Fibres:
Ø = 250 µm

Pixels belong to different detector channels

Photon can create signal (fired pixels are red)

Particle creates photons in each fiber

SiPM array

Readout by dedicated 128 ch.
40 MHz PACIFIC chip
• 3 thresholds (2 bits)
• sum threshold (FPGA)
T-stations upgrade: Fibre Tracker (FT)

- 3 stations of X-U-V-X (±5° stereo angle) scintillating fibre planes
- every plane made of 5 layers of Ø=250 μm fibres, 2.5 m long
- 40 MHz readout and Silicon PMs at periphery

Benefits of the SciFi concept:
- a single technology to operate
- uniform material budget
- SiPM + infrastructure outside acceptance
- fine channel granularity of 250 μm
- x-position resolution of 50 – 75 μm
- high hit detection efficiency (≥ 99%)
- fast pattern recognition for HLT

Challenges → radiation environment
- ionization damage to fibres → tested ok
- neutron damage to SiPM → operate at -40°C
Tracking performance

Performance of the forward pattern recognition algorithm

Efficiency for $B_s \rightarrow \Phi \Phi$ events at upgrade conditions: current and upgraded T-stations

Ghost rate for long tracks for $B_s \rightarrow \Phi \Phi$ events: without UT and with UT ($\geq 3$ hits)

→ improve tracking performance at upgrade luminosity with Fibre Tracker

→ reduce significantly the ghost rate using the Upstream Tracker information
Expected CPU budget with upgraded Event Filter Farm: \(~13\) ms (10 x current CPU farm)

Performance of HLT tracking with upgraded VELO, UT and FT:

<table>
<thead>
<tr>
<th>Tracking Algorithm</th>
<th>No GEC</th>
<th>GEC = 1200</th>
</tr>
</thead>
<tbody>
<tr>
<td>VELO tracking</td>
<td>2.3</td>
<td>2.0</td>
</tr>
<tr>
<td>VELO-UT tracking</td>
<td>1.4</td>
<td>1.3</td>
</tr>
<tr>
<td>Forward tracking</td>
<td>2.5</td>
<td>1.9</td>
</tr>
<tr>
<td>PV finding</td>
<td>0.40</td>
<td>0.38</td>
</tr>
<tr>
<td>Total @29 MHz</td>
<td>5.6</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>6.6</td>
<td>5.4</td>
</tr>
</tbody>
</table>

\(\rightarrow\) leaves \(~6-7\) ms for a trigger decision

GEC (Global Event Cut) \(\rightarrow\) multiplicity cut to remove pathological events (e.g. hit multiplicity of sub-detector)

\(\rightarrow\) high efficiency (even with GEC)
Particle identification with Calorimeters

\[ A_{CP} (B^0 \to K^*\gamma) = (0.8 \pm 1.7 \pm 0.9) \% \]

and worlds best branching ratio measurement:
\[ BR(B_s \to \Phi\gamma) = (3.5 \pm 0.4) \cdot 10^{-5} \]

with invariant mass resolution \( \sim 94\,\text{MeV/c}^2 \)

Typical \( \pi^0 \) mass resolution \( \sim 7\text{-}10\,\text{MeV/c}^2 \)
(depending on number of converted photons)
Calorimeters upgrade

Radiation damage and occupancies:

- Preshower and SPD removed
- HCAL modules ok up to \( \sim 50 \text{ fb}^{-1} \)
- Irradiation tests show that most exposed ECAL modules resist up to \( \sim 20 \text{ fb}^{-1} \) \( \rightarrow \) LS3

<table>
<thead>
<tr>
<th>E beam, GeV</th>
<th>module #1 (irradiated 2 Mrad)</th>
<th>module #2 (not irradiated)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>light yield</td>
<td>resolution, %</td>
</tr>
<tr>
<td>50</td>
<td>583±12</td>
<td>2.16±0.04</td>
</tr>
<tr>
<td>100</td>
<td>576±12</td>
<td>1.57±0.03</td>
</tr>
<tr>
<td>120</td>
<td>571±12</td>
<td>1.36±0.03</td>
</tr>
</tbody>
</table>

40 MHz readout electronics:

- Reduce photomultiplier gain
- Two interleaved integrators at 20 MHz
- Fully differential implementation
- Track and Hold

Most inner ECAL modules around beam-pipe can be replaced.
Particle identification with Muon System

MWPC
5 stations
M1 to M5

high detection efficiency: \( \varepsilon(\mu) = (97.3 \pm 1.2)\% \)

low misidentification rates:
\( \varepsilon(p \to \mu) = (0.21 \pm 0.05)\% \)
\( \varepsilon(\pi \to \mu) = (2.38 \pm 0.02)\% \)
\( \varepsilon(K \to \mu) = (1.67 \pm 0.06)\% \)
Muon System upgrade

Modifications due to higher luminosity and 40 MHz readout:

- remove M1 due to too high occupancies
- keep on-detector electronics (CARIOCA), already at 40 MHz readout
- new off-detector electronics for an efficient readout via PCIe40 R/O boards
- additional shielding behind HCAL to reduce the rate in the inner region of M2

![Diagram showing the structure of the muon system](image)

- **on-detector electronics**
- **off-detector electronics**
Status of the LHCb upgrade

- LHCb upgrade fully approved by CERN management for installation in 2018/19

- All TDRs submitted (2 approved, 1 under recommendation, 1 under review)

- MoU for Common Projects submitted for signature to Funding Agencies
due to its excellent detector performance LHCb is producing world best measurements in the b and c-quark sector

by 2018 with ~8 fb\(^{-1}\) LHCb will find or rule-out large sources of flavour symmetry breaking at the TeV scale

the LHCb upgrade is mandatory to reach experimental precisions of the order of the theoretical uncertainties

an efficient and selective software trigger with access to the full detector information at every 25 ns bunch crossing will allow to collect the necessary \(\geq 50\) fb\(^{-1}\) within \(\sim 10\) years

the LHCb upgrade is fully approved, with the last TDR under review

the detector upgrade to 40 MHz readout sustaining a levelled luminosity of \(2 \cdot 10^{33}\) cm\(^{-2}\)s\(^{-1}\) at 25 ns bunch spacing will be ready for installation in 2019 and operational at the beginning of 2020