LHCb Upgrades

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On behalf of the LHCb collaboration
Overview

- **Motivation.**
  - Flavour physics @ HL-LHC.
- **Upgrade I.**
  - Status of installation.
- **Upgrade Ib.**
  - Consolidation plans.
- **Upgrade II.**
  - Plans & Design.
- **Summary.**
Why LHCb?

- Dedicated heavy flavour experiment at LHC.
  - Measure CP-violation in $b$-sector.
  - Study rare $b$- and $c$- hadron decays.
  - Exploit forward production of $b$-pairs with low angle.

✧ **Indirect searches for New Physics.**

- Physics program in Runs 1&2 was much much more.
  - Electroweak, QCD, direct searches, heavy ions.

✧ **General Purpose Detector in forward region.**
Why upgrade?

- Some hints of New Physics in LHC Runs 1 & 2.
  - Lepton flavour (non-)universality?
    - Semi-leptonic $B^0 \to D^{(*)-} l^+ \nu$ (tree level decay) – $R(D^*)$.
    - $b \to s l^+ l^-$ decays e.g. $B^0 \to K^{(*)0} l^+ l^-$ (FCNC decays) – $R(K)$, $R(K^*)$.
  - Angular analysis of $K^* \mu^+ \mu^- $.
  - No “discovery” but coherent set of discrepancies w.r.t. Standard Model.

- More data to further challenge theoretical predictions.
  - Precision tests with very rare decays ($BR < 10^{-9}$).

- Limited by Level-0 hardware trigger.
  - Maximum rate is 1.1 MHz.

- Higher luminosities:
  - Trigger yield saturates.
  - Harder cuts on $E_T$ and $p_T$.
  - No real gain in statistics.

- Higher occupancy.
  - Degraded detector performance.
  - Radiation damage of detectors.
Separation of primary and secondary vertices.
- Impact parameter resolution: \((15 + 29/p_T[\text{GeV}]) \text{ } \mu m\).

Proper time resolution.
- Decay time resolution: \(~45 \text{ fs} (B_s \rightarrow J/\psi \phi & B_s \rightarrow D_s \pi)\).

Excellent momentum resolution:
- \(\Delta p / p = 0.5\% (<20 \text{ GeV})\) to \(1.0\% (200 \text{ GeV})\).

Particle Identification:
- Separation between \(\gamma, e^\pm, \mu^\pm, \pi, K, p\).

Trigger Selection:
- Efficient trigger for leptonic and hadronic final states.
- Fast reconstruction of primary and secondary vertices.

Run 1&2 performance is benchmark for Upgrades
CKM Measurements

LHC-B

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A Dedicated LHC Collider Beauty Experiment for Precision Measurements of CP-Violation

Figure 2.1: Limits on the CKM parameters (1σ) ρ and η for \( m_t = 174 \text{ GeV} \). The annular region cen-

\[
V_{\text{CKM}} = 
\begin{pmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{pmatrix}
\]

Matrix is unitary: 
\[ V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0 \]

\[ \alpha = \arg \left( -\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*} \right), \quad \beta = \arg \left( -\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*} \right), \quad \gamma \equiv \arg \left( -\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} \right). \]
CKM Measurements

LHC-B

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1995

Figure 2.1: Limits on the CKM parameters (1σ) ρ and η for m_t = 174 GeV. The annular region cen-

\[ V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \]

σ_γ ≈ 5° (2019) \rightarrow 1° (Phase 1) \rightarrow 0.35° (Phase 2)

LHCb (300 fb^{-1}), Belle-II (50 ab^{-1})
ATLAS & CMS (3000 fb^{-1})


## Physics Reach

<table>
<thead>
<tr>
<th>Observable</th>
<th>Current LHCb</th>
<th>LHCb 2025</th>
<th>Belle II</th>
<th>Upgrade II</th>
<th>ATLAS &amp; CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_K$ ($1 &lt; q^2 &lt; 6 \text{GeV}^2c^4$)</td>
<td>0.1</td>
<td>0.025</td>
<td>0.036</td>
<td>0.007</td>
<td></td>
</tr>
<tr>
<td>$R_{K^+}$ ($1 &lt; q^2 &lt; 6 \text{GeV}^2c^4$)</td>
<td>0.1</td>
<td>0.031</td>
<td>0.032</td>
<td>0.008</td>
<td></td>
</tr>
<tr>
<td>$R_{\phi}$, $R_{pK}$, $R_{\pi}$</td>
<td>--</td>
<td>0.08, 0.06, 0.18</td>
<td>--</td>
<td>0.02, 0.02, 0.05</td>
<td></td>
</tr>
</tbody>
</table>

**CKM tests**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Current LHCb</th>
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<th>Belle II</th>
<th>Upgrade II</th>
<th>ATLAS &amp; CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma$, with $B_s^0 \rightarrow D_s^+ K^-$</td>
<td>$(+17)_3^{-22}^o$</td>
<td>4$^o$</td>
<td>--</td>
<td>1$^o$</td>
<td>--</td>
</tr>
<tr>
<td>$\gamma$, all modes</td>
<td>$(+5.0)_3^{-5.8}^o$</td>
<td>1.5$^o$</td>
<td>1.5$^o$</td>
<td>0.35$^o$</td>
<td>--</td>
</tr>
<tr>
<td>$\sin 2\beta$, with $B^0 \rightarrow J/\psi K_S^0$</td>
<td>0.04</td>
<td>0.011</td>
<td>0.005</td>
<td>0.003</td>
<td>--</td>
</tr>
<tr>
<td>$\phi_s$, with $B_s^0 \rightarrow J/\psi \phi$</td>
<td>49 mrad</td>
<td>14 mrad</td>
<td>--</td>
<td>22 mrad</td>
<td>--</td>
</tr>
<tr>
<td>$\phi_s$, with $B_s^0 \rightarrow D_s^+ D_s^-$</td>
<td>170 mrad</td>
<td>35 mrad</td>
<td>--</td>
<td>9 mrad</td>
<td>--</td>
</tr>
<tr>
<td>$\phi_s^s$, with $B_s^0 \rightarrow \phi \phi$</td>
<td>154 mrad</td>
<td>39 mrad</td>
<td>--</td>
<td>11 mrad</td>
<td>Under study</td>
</tr>
<tr>
<td>$a_s^s$</td>
<td>$33 \times 10^{-4}$</td>
<td>$10 \times 10^{-4}$</td>
<td>--</td>
<td>$3 \times 10^{-4}$</td>
<td>--</td>
</tr>
<tr>
<td>$</td>
<td>V_{ub}</td>
<td>/</td>
<td>V_{cb}</td>
<td>$</td>
<td>6%</td>
</tr>
</tbody>
</table>

### $B_s^0, B^0 \rightarrow \mu^+ \mu^-$

| $B(B^0 \rightarrow \mu^+ \mu^-)/B(B_s^0 \rightarrow \mu^+ \mu^-)$ | 90% | 34% | -- | 10% | 21% |
| $\tau_B^B \rightarrow \mu^+ \mu^-$ | 22% | 8% | -- | 2% | -- |
| $S_{\mu \mu}$ | -- | -- | -- | 0.2 | -- |

### $b \rightarrow c\ell^- \bar{\nu}_l$ LUV studies

| $R(D^*)$ | 0.026 | 0.0072 | 0.005 | 0.002 | -- |
| $R(J/\psi)$ | 0.24 | 0.071 | -- | 0.02 | -- |

**Charm**

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</tr>
</thead>
<tbody>
<tr>
<td>$\Delta A_{CP}(KK - \pi \pi)$</td>
<td>$8.5 \times 10^{-4}$</td>
<td>$1.7 \times 10^{-4}$</td>
<td>5.4 $\times 10^{-4}$</td>
<td>3.0 $\times 10^{-5}$</td>
<td>--</td>
</tr>
<tr>
<td>$A_{\Gamma}$ ($\approx x \sin \phi$)</td>
<td>$2.8 \times 10^{-4}$</td>
<td>$4.3 \times 10^{-5}$</td>
<td>3.5 $\times 10^{-4}$</td>
<td>1.0 $\times 10^{-5}$</td>
<td>--</td>
</tr>
<tr>
<td>$x \sin \phi$ from $D^0 \rightarrow K^+ \pi^-$</td>
<td>$13 \times 10^{-4}$</td>
<td>$3.2 \times 10^{-4}$</td>
<td>4.6 $\times 10^{-4}$</td>
<td>$8.0 \times 10^{-5}$</td>
<td>--</td>
</tr>
<tr>
<td>$x \sin \phi$ from multibody decays</td>
<td>--</td>
<td>$(K_3 \pi) 4.0 \times 10^{-5}$</td>
<td>$(K_s^0 \pi \pi) 1.2 \times 10^{-4}$</td>
<td>$(K_3 \pi) 8.0 \times 10^{-6}$</td>
<td>--</td>
</tr>
</tbody>
</table>

*Taken from Physics case for an LHCb Upgrade II (CERN-LHCC-2018-027)*
Expression of Interest for an LHCb Upgrade

The LHCb Collaboration

Abstract

There is a growing international understanding that future flavour physics experiments will be required in the second half of the next decade to either study the flavour structure of new particles discovered at the LHC or to probe new physics at the multi-TeV scale. Here we present an expression of interest of the LHCb collaboration for an upgrade of the LHCb detector after it will have collected a data sample of about 10 fb$^{-1}$.

We envisage this upgrade to enable the LHCb experiment to operate at 10 times the design luminosity, i.e. at about $2 \times 10^{33}$ cm$^{-2}$s$^{-1}$, to improve the trigger efficiency for hadronic decays by a factor of two and to collect a data sample of $\sim 100$ fb$^{-1}$. In this document we briefly describe the motivation for an LHCb upgrade. We then outline the R&D programme necessary to evaluate the required technologies for a high luminosity LHCb upgrade, which must take place over the next few years.

Conditions:
- Luminosity: $2 \times 10^{33}$ cm$^{-2}$s$^{-1}$ (inst.), 50 fb$^{-1}$ (int.)
- 5.2 visible interactions / crossing.

Challenge:
- Maintain current reconstruction performance in harsher environment.
- Read out the complete detector at 40 MHz.
LHCb Upgrade I

Tracking System: NEW DETECTORS!

- Pixels
- Si Strips

Scintillating fibres read out with SiPMs

Muon system

- M1 removed.
- NEW READ-OUT!

Calorimetry
- SPD/PS removed – no L0 trigger.
- Operate PMTs at lower gain.
- NEW READ-OUT!

Ring Imaging Cherenkov detectors:
- Optical system will be modified in RICH1.
- NEW PHOTON DETECTORS AND READ-OUT!
- RTA is integral part of DAQ chain in upgrade data processing.
  - Offline reconstruction in HLT2 à la Run 2.
- TURBO model for exclusive selections.
  - High-level physics objects directly from the HLT → small fraction of raw event size.
- HLT1 reconstruction will run on GPUs.

25th May 2014
- Data centre on surface.
  - Event Filter Farm and Event Builder network.
- Long distance optical fibres.
  - 19008 fibers installed (0.25% broken).
- Common read-out boards (PCle40).
  - Large FPGA with 1.15M cells.
  - 48 bi-directional links (10 Gbit/s).
  - Three flavours of firmware.
- GPUs in event builder PCs.

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Two retractable halves
- 3.5 mm from beam when closed.
- First measurement at 5.1 mm.

Operates in secondary vacuum.
- Aluminium R.F. foils separate detector from beam vacuum.
- Milled to 250 μm thick then chemically etched to 150 μm.

52 hybrid-pixel modules.
- 41M pixels covering total area ~ 1.2 m².
- Hybrid pixel detector.
  - 200 μm n-on-p sensor tiles.
- New read-out ASIC (VeloPix).
  - 256x256 pixel array (55 μm x 55 μm)
  - 12 per module.
- Evaporative CO$_2$ cooling in silicon micro-channel substrates (T < −20°C).
- High bandwidth:
  - 20 Gbit/s in hottest ASICs with ~ 3 Tbit/s overall.
- Non-uniform irradiation:
  - $8 \times 10^{15}$ n$_{eq}$/cm$^2$ which falls as $\sim r^{-2.1}$.

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Silicon micro-strip detector.
- Four layers (x, u, v, x) upstream of magnet.
- Finer granularity, closer to beam.

Four types of sensors.
- n- and p-type with 512 or 1024 strips.
- 320/250 μm thick; 190/95 μm pitch.

Modules mounted on double-sided staves.
- 68 staves / 968 sensors.
- Bi-phase CO₂ cooling pipe integrated in stave.

New read-out ASIC (SALT).
- 128 channels with 6-bit ADC.
- Pedestal & common-mode subtraction, zero-suppression.
- Output up to 6 SLVS e-links per ASIC.
- 1048 4-asic read-out sectors = 4192 ASICs.

Read-out electronics mounted on detector frame.
- Silicon micro-strip detector.
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- Read-out electronics mounted on detector frame.
Scintillating Fibre Tracker

- Scintillating fibres read out with SiPMs.
  - 2.4 m long, 250 μm diameter, 6 layers of fibres in module.
  - 12 detection planes \( - 3 \times (x, u, v, x) \).

- SiPMs outside acceptance.
  - 128 channels with width 250 μm
  - Require cooling to \(-40^\circ C\) (neutron radiation).

- New ASIC for read-out (PACIFIC).
  - 64 channels, 130 nm CMOS (TSMC).
  - ADC with three hardware thresholds.

- Clustering on FPGA board in front-end box.
Particle ID

Cherenkov detectors:
- RICH 1: $\text{C}_4\text{F}_{10}$ (10 – 65 GeV/c).
  - Replace everything (mirrors, gas enclosure, quartz windows).
- Replace Hybrid Photon Detectors (HPDs) with Multi Anode Photomultiplier Tubes (MaPMTs).
- New 8-channel read-out ASIC (CLARO).

Calorimeters & Muon System
- Remove unnecessary detectors.
- Replace read-out electronics.

MaPMTs (Hamamatsu)

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**UPGRADE II**

**Conditions:**
- Luminosity: $1.5 \times 10^{34}$ cm$^{-2}$s$^{-1}$ (inst.), 300 fb$^{-1}$ (int.)
- 40 visible interactions / crossing.

**Challenge:**
- Maintain current reconstruction performance in much, much harsher environment.
- Develop detectors with timing information for tracking & Particle ID.
LHCb Upgrade II

Tracking System: NEW DETECTORS!

Smaller pixels, thinner sensors. $\sigma_t < 200$ ps / hit.

SciFi Tracker + Silicon detectors in central region

Silicon Strips

Magnet stations

Muon system:

MPGD (μ-RWELL), modified shielding

Replace HCAL with 1.7m iron

TORCH: t.o.f. PID ($p < 10$ GeV)

MCP-PMTs with $\sigma_t \approx 15$ ps

ECAL with finer segmentation

Timing plane with $\sigma_t \approx 20 – 50$ ps
Detector Technologies

Lots of R&D across collaboration.

- SPACAL with crystal fibres.
- CMOS tracker chip in design.
- Silicon with timing capabilities.
- Photon sensors with timing.
- New MPGDs for high-rate muon detection.

Prototype CALO cell

MCP-PMTs for TORCH
Summary

CONCLUSIONS
Summary

Upgrade I (2008 – now):
- Significant progress made by all sub-detectors.
  - Installation is underway!
  - All sub-detectors (were) in full production mode.
- Schedule is (increasingly) challenging.
  - Impact of COVID-19 continuously being assessed.

Upgrade II (2017 – ??):
- Lots of active R&D across collaboration.
- Sub-detectors developing baseline designs.
- Framework TDR expected in 2021.
Merci à tous!
MORE?

BACK UP
UPGRADE 1

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Target Luminosity

$$L_{\text{inst.}} = 4 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1} \quad \mu \approx 1$$

$$L_{\text{inst.}} = 2 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1} \quad \mu \approx 5.2$$

$$L_{\text{inst.}} = 1 - 2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1} \quad \mu \approx 28 - 55$$

* $\mu$ is average number of visible $pp$ interactions per bunch crossing.
CKM Measurements

LHC-B

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Figure 2.1: Limits on the CKM parameters (1σ) ρ and η for \( m_t = 174 \text{ GeV} \). The annular region cent-

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\end{pmatrix}
\]

LHCb (23fb\(^{-1}\)), Belle-II (50 ab\(^{-1}\))
ATLAS & CMS (300 fb\(^{-1}\))

\( \sigma_\gamma \approx 5^\circ \text{ (2019)} \rightarrow 1^\circ \text{ (Phase 1)} \rightarrow 0.35^\circ \text{ (Phase 2)} \)
- Remove Level-0 hardware trigger.
  - Read out every bunch crossing (40 MHz).
  - Replace all front-end electronics.
- Trigger-less read-out system.
  - Full software trigger for every 25 ns bunch crossing.
- Higher occupancy.
  - Redesign and replace tracking detectors.
- Installation during Long Shutdown 2 (on-going).

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VELO II

- Hybrid pixel detector.
  - Easier pattern recognition.
  - Thinner sensors (300 μm → 200 μm).
- Move closer to beam
  - First measurement: 8.13 mm → 5.1 mm.
- New RF foil.
  - Reduce material before first measurement.
- New ASIC (VeloPix)
  - Based on Medipix/TimePix.
  - 256x256 (55 μm x 55 μm)
  - 12 per module.
- Non-uniform irradiation.
  - Extremely high data rates.
  - Micro-channel cooling in substrate.
Upstream Tracker

- Near-detector electronics outside acceptance.
  - Distributes TFC&ECS signals.
  - Collects serial data from ASICs (320 Mbps).
  - Transmits optical serial data via GBTx/VTTx (~4.8 Gbps).
  - Connected to stave via pigtail flex cables.

- Two versions of read-out ASIC (SALT).
  - Problems found in previous iterations have been solved.
    - Analogue power issues, 40 MHz oscillations.
  - 4- (8-) ASIC modules assembled with SALT v3.5 (v3.8).

- Full read-out chain validated in system test.
  - First tests with final powering and grounding scheme.
  - CO₂ cooling tests at −30°C.
SciFi Tracker

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RICH

**RICH1:** Change everything but the magnetic shielding

- mirrors, gas enclosure, quartz windows
- Photon detectors, electronics, detector mechanics

=> 22 columns

**RICH2:** Change only detectors

- Photon detectors, electronics, detector mechanics

=> 24 columns

MAPMT

R13743

R13742

48 mm x 48 mm OuterRICH2

23 mm x 23 mm RICH1+innerRICH2

Elementary Cell
EC = 4 or 1 xMAPMT +Baseboards

A column = 6 PDMs (on a “cold bar”)

Photon Detector Module
PDM = 4 ECs
Installation

RICH 1 mechanics installed:
- Magnetic shielding shelves, MaPMT supports, gas enclosure.

Detector Services:
- 100% of long distance copper cables installed.
- 100% of optical fibres installed & tested.
  - Few fibres with power loss > threshold.
- 100% of long distance pipes installed.

CO₂ cooling plants (VELO & UT):
- CO₂ cooling plants and distribution boxes installed.
- Connections and first tests performed.
- Cleaning required to remove “oil”.

Services

CO₂ cooling
Each event builder server has two GPU slots = 500 GPUs.

HLT1 *must* run at visible collision rate (30 MHz).
- Minimum throughput rate per GPU is 60 kHz.

See presentation by Dorothea Vom Bruch for more details (27/5).
Magnet tracking stations

Time Of internally Reflected CHERenkov light (TORCH).

UPGRADE 1B
Magnet Stations

- Tracking stations on internal walls of magnet.
  - Reconstruction low momentum tracks.
- Scintillator bars read out with SiPMs outside acceptance.
  - Re-use existing SciFi Tracker electronics (ASIC, read-out boards, etc).

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- **Time Of internally Reflected CHerenkov light.**
  - Large area time-of-flight detector.
  - Provide PID in momentum range 1 – 10 GeV/c.
- **Cherenkov light produced in quartz plates.**
  - Photons travel to detector plane via total internal reflection.
- **Focusing block focuses image on detection plane.**
- **Multichannel plate PMTs with 35 ps time resolution.**
  - Resolutions of 88 – 130 ps achieved in test beams.
- **Possible installation in Upgrade 1b.**

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UPGRADE 2
**Radiation Environment**

- **Expected dose / fluence:**
  - **VELO:** $5 \times 10^{16} \text{ n}_{\text{eq}} / \text{cm}^2$.
  - **ECAL:** 1 MGy; $\leq 5 \times 10^{15} \text{ n}_{\text{eq}} / \text{cm}^2$.
  - **Tracker:** $3 \times 10^{14} \text{ n}_{\text{eq}} / \text{cm}^2$ (silicon).
  - **SiPMs:** $13.2 \times 10^{11} \text{ n}_{\text{eq}} / \text{cm}^2$ (run 3&4).

- **Non-uniform irradiation profile.**
- **Need radiation hard detectors and/or extreme cooling solutions.**
- **Make hot-swappable detectors!**

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- Reconstruction of PV critical for LHCb.
  - 40 visible interactions / crossing @ $1.5 \times 10^{34}$ cm$^{-2}$s$^{-1}$.
- Add timing information.
  - Reduces combinatorics and minimises PV mis-association.
- PV mis-association rate ~ 20% without timing.
  - Reduce to ~5% with timing precision between 50 – 100 ps.
VELO III

- Silicon sensors with timing capability.
  - Aim for 50 ps per hit $\rightarrow$ 15 ps per track.
  - Several candidates: LGAD, 3D, MAPS.

- Higher occupancy:
  - Reduce pixel size
  - $55 \times 55 \mu m^2 \rightarrow 27.5 \times 27.5 \mu m^2$.

- Minimise material.
  - Thinner sensors.
  - Remove r.f. foil and operate in primary vacuum.

- Fluence $\sim 8 \times 10^{16} n_{eq} / cm^2$.
  - Require radiation hard sensors.
Downstream Tracking

- Add silicon detectors in central region.
  - Segmentation in y-direction $\rightarrow$ reduce ghost rate.
- Replace SciFi modules around beam-pipe in LS3.
  - Hybrid modules with shorter fibres.
  - Silicon sensors around beam-pipe (HV-CMOS).
- New radiation hard fibres being studied.
- Cryogenic cooling proposed for SiPMs ($-80^\circ$C).
LHCb detector

2 < \eta < 5

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- Two retractable halves
  - 5 mm from beam when closed.
  - 30 mm during injection.
  - First measurement at 8.13 mm.
- Operates in secondary vacuum.
  - 300 μm aluminium foils separates detector from beam vacuum.
- 21 R-Φ modules per half.
  - Silicon microstrip sensors.
  - Pitch: 38 – 101 μm.
- Best resolution: 4 μm!
**LHCb Tracker**

**Silicon Tracker:**
- Silicon micro-strip detectors covering areas closest to the beam pipe.
- Pitch: 183 μm (TT), 198 μm (IT).
- Thickness: 500 μm (TT), 320/410 μm (IT).
- Strips up to 37 cm long.
- Resolution ≈ 50 μm.

**Outer Tracker:**
- Gaseous straw tube detector.
- 12 detection layers (~ 4 x 6 m²).
- 53760 straw tubes (2.4 m long, 4.9 mm diameter).
- Gas mixture: Ar/CO₂/O₂ (70%/28.5%/1.5%).
- Nominal operating voltage is 1550 V.
- Resolution ≈ 200 μm.