LHCb status report

Elisa Minucci

on behalf of the LHCb collaboration

154th LHCC meeting
Open Session

7th June 2023
The LHCb U1 upgrade

- Software only trigger
  - GPU HLT1
  - CPU HLT2

- New tracking stations

- Upgraded gas injection system
  - (SMOG2)

- New pixel
  - VELO

- RICH1 new optics
  - RICH1&2 new PMTs and readout

- Upgrade calo front-end electronics
  - removed PS/SPD

- Upgraded muon front-end electronics,
  - removed M1

- 90% of detector channels upgraded
- Complete replacement of readout electronics
- New DAQ & online system @ 30 MHz

\[ L_{\text{peak}} = 2 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1} \] (x5 w.r.t Run1)
Run 3: Where we are now

**Completed**

**Sub-detectors installation**

LHCb upgrade I paper published
CERN seminar 16th June

**Sub-detectors & data flow commissioning**

Commissioning started during 2022
Important milestones achieved

**Ongoing**

**Study of detector performance**

First checks on data collected in 2022
Important to address the detector performance

2023 data @ 6.8 TeV
Upstream Tracker

- Part of the software trigger
- Reduce track combinatorics (ghosts)
- Reconstruct long-lived particles

UT successfully closed before the start of 2023 run!
Installation and closure of the UT detector within 22/23 YETS have been a challenging target:

- Mechanical installation in the cavern
- CO$_2$ cooling commissioning
- Cable chain population and power test
- Test on data-links
- Detector closure

Detector closer to the beam pipe w.r.t previous detector to increase geometrical acceptance and tracking performance

Detector closure, extremely delicate procedure
Upstream Tracker

Commissioning started → a lot of progresses since the beginning of 2023 run

**Firmware**
4 different flavour
2 flavours currently being deployed on the real hardware, allowing to fix issues and bugs

**Control**
80% ready → can be used by expert to monitor data taking

**Software**
Decoding/reconstruction well advanced
Detector calibrations need to be automated
Integration to general software well advanced

**CO₂ cooling running smoothly at 0°C**

Data collected with 4x3 firmware

1°C milestone achieved
Run taken on May 12th
LHC vacuum incident in LHCb VELO (10\textsuperscript{th} January 2023)

Primary vacuum (beam) and secondary vacuum (VELO) separated by a thin RF foil  
Safety vacuum balance $\Delta P < 10\text{mbar}$

- relay failure lead to loss of control of protection system  
  - Safety valve not open  
  - Pressure balancing in the wrong direction ($\Delta P \approx 200\text{mbar}$)

VELO modules and cooling not damaged and operational

- First estimation of RF deformation using simulations  
- Measurement of RF deformation with tomography  
- Inspection

RF foil deformed towards the beam vacuum

Huge thanks to the LHC vacuum team for their help in recovering from the vacuum incident!
VELO Tomography

Data from 450GeV and 6.8TeV (400b fills)
SMOG2 injection extremely useful to enhance the material interaction coverage (thanks to support of TE-VSC and SMOG team)
Tomography results in agreement with measurement from collimation group

VELO commissioning is progressing

VELO will not be fully closed during the 2023 run → final position has been defined: VELO opened by 16 mm with respect to the nominal fully close position (pending further test to be performed in TS1)

RF foil will be replaced during the 23/24 YETS
Plans for 2023 data taking

First period (Before TS1)
1) Priority to sub-detectors recommissioning
   - Monitoring
   - Firmware performance
   - Timing scans
   - Stability of the systems
   - Debugging
   - Data quality (efficiency, noise, …)
   - Testing

2) Regularly plan time to probe full system (including trigger & data processing)

Second period (between TS1 and Pb–Pb run)
- Dedicated to global commissioning
- Physics program (depending on the final position of VELO)

Third period (Pb–Pb run)
- Physics program

Output of HLT1 on 17 May with increasing luminosity

Reached designed data rate @ nominal luminosity (mu ~ 6–7)

GPU HLT1 commissioned @ nominal rate and luminosity!
Validating detector performance

**RICH**

**RICH 1**
Upstream of the magnet, 2.6 < p < 60 GeV/c

- $\sigma(\Delta \theta_{\text{Cherenkov}}) = (1.106 \pm 0.004) \times 10^{-3}$ rad
- $\sigma(\Delta \theta_{\text{Cherenkov}})_{\text{Run 2}} = (1.640 \pm 0.003) \times 10^{-3}$ rad

**RICH 2**
Downstream of the magnet, 15 < p < 100 GeV/c

- $\sigma(\Delta \theta_{\text{Cherenkov}}) = (0.623 \pm 0.002) \times 10^{-3}$ rad
- $\sigma(\Delta \theta_{\text{Cherenkov}})_{\text{Run 2}} = (0.650 \pm 0.001) \times 10^{-3}$ rad

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**2022 data**

**LHCb-Figure-2023-007**
Validating detector performance

Improvement in the di-photon mass peak and mass resolution around the $\pi^0$ mass thanks to inter-cell calibration and time alignment
Validating detector performance

SMOG2

Mass resolutions close to the expectations from Monte Carlo

$\Lambda^0 \to p\pi^{-}$ in p–H

$J/\psi \to \mu^+\mu^-$ in p–Ar

Primary vertex longitudinal coordinate for vertices reconstructed by HLT1.
Validating detector performance

**HLT1**

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

- Full model
- \( K_s^0 \rightarrow \pi^+\pi^- \)
- Combinatorial bkg

LHCb preliminary 2022 (240 nb\(^{-1}\))

<table>
<thead>
<tr>
<th>( N_{sig} )</th>
<th>( \pm N_{bkg} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>531771</td>
<td>( \pm 798 )</td>
</tr>
<tr>
<td>50469</td>
<td>( \pm 360 )</td>
</tr>
</tbody>
</table>

\( m(\pi^+\pi^-) \) [MeV/c\(^2\)], Candidates / 1 (MeV/c\(^2\))

**HLT2**

\[ J/\psi \rightarrow \mu^+\mu^- \]

\[ B^+ \rightarrow J/\psi(e^+e^-)K^+ \]

\[ D^0 \rightarrow K^-\pi^+ \]

**2022 data**

LHCb-Figure-2023-005

LHCb-Figure-2023-010, LHCb-Figure-2023-011, LHCb-Figure-2023-017
# Physics highlights from Run1+2

<table>
<thead>
<tr>
<th>Paper</th>
<th>Title</th>
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</thead>
<tbody>
<tr>
<td>PAPER-2022-042</td>
<td>Search for CP violation in the decays $D^+ \to K^+K^-K^+$ and $D_s \to K^+K^-K^+$</td>
</tr>
<tr>
<td>PAPER-2022-054</td>
<td>Observation of $B^+ \to J/\psi\eta K^+$</td>
</tr>
<tr>
<td>PAPER-2023-004</td>
<td>Search of $D^* \to \mu^+\mu^-$</td>
</tr>
<tr>
<td>PAPER-2023-001</td>
<td>Precision measurement of CPV in penguin-mediated decay $B_s \to \phi\phi$</td>
</tr>
<tr>
<td>PAPER-2022-050</td>
<td>Study of charmonium decays to $K_S K\pi$ in $B \to (K_S K\pi)K$</td>
</tr>
<tr>
<td>PAPER-2022-052</td>
<td>$R(D^*)$ with $\tau$ hadronic decays</td>
</tr>
<tr>
<td>PAPER-2022-041</td>
<td>$\Xi_c^+$ production in pPb at 8.16 TeV</td>
</tr>
<tr>
<td>PAPER-2023-003</td>
<td>Measurements of the branching fractions of the decay modes $B_s \to D^{(*)}\phi$</td>
</tr>
<tr>
<td>PAPER-2022-053</td>
<td>$\Xi_b$ and $\Omega_b$ mass and production</td>
</tr>
<tr>
<td>PAPER-2022-047</td>
<td>Associated Production of Prompt $J/\psi$ and $\Upsilon$ at $\sqrt{s} = 13$ TeV</td>
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Preliminary results since the March 2023 LHCC

<table>
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<tr>
<td>PAPER-2023-002</td>
<td>Bose Einstein Correlation in pPb</td>
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<tr>
<td>PAPER-2023-005</td>
<td>Search for local CPV in $D^0 \to \pi^-\pi^+\pi^0$ using the energy test with Run 2</td>
</tr>
<tr>
<td>PAPER-2023-006</td>
<td>Prompt $D^+/D_s^+$ meson production in pPb collisions at $\sqrt{s_{NN}}=5.02$ TeV at LHCb</td>
</tr>
<tr>
<td>PAPER-2023-007</td>
<td>Measurement of the CP asymmetry in $B^- \to K^+K^-\pi^-$ decays to two open charm mesons</td>
</tr>
<tr>
<td>PAPER-2023-008</td>
<td>Observation of new baryons in the $\Xi^-\pi^+\pi^-$ and $\Xi^0\pi^+\pi^-$</td>
</tr>
<tr>
<td>PAPER-2023-013</td>
<td>CP violation in $B \to \psi K_s$ decays</td>
</tr>
<tr>
<td>PAPER-2023-016</td>
<td>Measurement of the $\phi_s$ in $B_s \to J/\psi KK$</td>
</tr>
</tbody>
</table>
CP violation in B decays

CP violation observables can be accessed at

\[ e^+e^- \text{ colliders} \]

only \( B_{u,d} \) are produced

2001 CP violation has been established (and confirmed) by BaBar and Belle measuring \( \sin 2\beta \neq 0 \) from \( B^0 \rightarrow J/\psi K_s \)

Leading to the noble prize to Kobayashi and Maskawa

Hadron colliders

Study \( B_{u,d} \) system

+ unique opportunity to study \( B_s \) system, and

thus access different CP violation observables

2001

2021
CP violation in B decays

There are 3 types of CP violation

- CP violation in mixing
  \[ P(B^0 \rightarrow \bar{B}^0) \neq P(B^0 \rightarrow B^0) \]

- CP violation in decay
  \[ P(B^0 \rightarrow f_{CP}) \neq P(B^0 \rightarrow f_{CP}) \]

- CP violation in interference between decay and mixing
  \[ P(B^0 \rightarrow f_{CP}) \neq P(B^0 \rightarrow \bar{B}^0 \rightarrow f_{CP}) \]
CP violation in B decays

There are 3 types of CP violation:

- CP violation in mixing: \( P(B^0 \rightarrow B^0) \neq P(B^0 \rightarrow \bar{B}^0) \)
- CP violation in decay: \( P(B^0 \rightarrow f_{CP}) \neq P(\bar{B}^0 \rightarrow f_{CP}) \)
- CP violation in interference between decay and mixing: \( P(B^0 \rightarrow f_{CP}) \neq P(\bar{B}^0 \rightarrow f_{CP}) \)

Time-dependent CP asymmetry:

\[
A^\text{CP}(t) = \frac{\Gamma(\bar{B}^0(t) \rightarrow f) - \Gamma(B^0(t) \rightarrow f)}{\Gamma(\bar{B}^0(t) \rightarrow f) + \Gamma(B^0(t) \rightarrow f)} = \frac{S \sin(\Delta m_d t) - C \cos(\Delta m_d t)}{\cosh(1/2 \Delta \Gamma_d t) + A_{\Delta \Gamma} \sinh(1/2 \Delta \Gamma_d t)}
\]

- \( b \rightarrow c\bar{c}s \) golden channels
- \( b \rightarrow s\bar{s}s \) pure penguin decay

Benchmark measurements to search for New Physics
Time dependent CP violation: measurement effects

Flavour tagging
Knowledge of the B meson flavour at production (t=0) is essential

<table>
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<tr>
<th>Decay Mode</th>
<th>$\sigma_t$ (fs)</th>
<th>$\varepsilon_{eff}$ (%)</th>
</tr>
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<tbody>
<tr>
<td>$B^0 \rightarrow \psi K^0_s$</td>
<td>$\sim 60$</td>
<td>(4.6-6.5)</td>
</tr>
<tr>
<td>$B_s^0 \rightarrow J/\psi K^+ K^-$</td>
<td>$\sim 43$</td>
<td>(4.2-4.4)</td>
</tr>
<tr>
<td>$B_s^0 \rightarrow \phi \phi$</td>
<td>$\sim 43$</td>
<td>(5.7-6.3)</td>
</tr>
</tbody>
</table>

B-factory larger effective tagging efficiency $\sim 30\%$

Large improvements for Run2 analyses

Decay–time resolution
Fundamental to resolve $B_s^0 - \bar{B}_s^0$ oscillations
Time dependent CP violation: \( \sin 2 \beta \)

Time dependent CP violation in \( b \rightarrow c\bar{c}s \) transitions

\[
B^0 \rightarrow J/\psi(\mu^+\mu^-)K_S(\pi^+\pi^-) \sim 306k
\]

\[
B^0 \rightarrow J/\psi(e^+e^-)K_S(\pi^+\pi^-) \sim 43k
\]

\[
B^0 \rightarrow \psi_2(\mu^+\mu^-)K_S(\pi^+\pi^-) \sim 24k
\]

\( A^{CP}(t) = \sin(2\beta) \sin(\Delta m_d t) \)

\[ \beta \equiv \arg[-(V_{td}V_{tb}^*/(V_{cd}V_{cb}^*)] \]

New result from Run2 data
(6 fb\(^{-1}\) @ 13 TeV)

Fit all channels together and each channel separately

Time dependent CP violation: \[ A^{CP}(t) = \sin(2\beta) \sin(\Delta m_d t) \]

\[ S^{Run2}_{\psi K_S} = 0.716 \pm 0.013_{\text{stat}} \pm 0.008_{\text{syst}} \]

\[ C^{Run2}_{\psi K_S} = 0.012 \pm 0.012_{\text{stat}} \pm 0.003_{\text{syst}} \]

LHCb Run2 is the most precise single measurement to date!

Current average

\[ \sin(2\beta)^{HFLAV,2021} = 0.699 \pm 0.017 \]

\[ \sin(2\beta) \equiv \sin(2\phi_C) \]
Time dependent CP violation: $\sin 2\beta$

Previous
Current average

$$\sin(2\beta)^{\text{HFLAV,2021}} = 0.699 \pm 0.017$$

New average

$$\sin(2\beta)^{\text{HFLAV,2023}} = 0.708 \pm 0.011$$

CP-violating NP requires precise measurement of SM benchmarks

$\sin 2\beta$
key measurement for NP searches

LHCb-PAPER-2023-013 in preparation
Time dependent CP violation: \( \phi_s^{c\bar{c}s} \)

Measurement of CP violation parameter in \( B_s^0 \to J/\psi (\mu^+\mu^-) K^+ K^- \) (around \( \phi(1020) \))

Angular analysis: final state is a mixture of CP-even and CP-odd components

\[
A_{CP}^{c\bar{c}s}(t) = \frac{\Gamma(B_s^0(t) \to f) - \Gamma(B_s^0(t) \to \bar{f})}{\Gamma(B_s^0(t) \to f) + \Gamma(B_s^0(t) \to \bar{f})} = \eta_f \sin \phi_s \sin(\Delta m_s t)
\]

\[\beta_s \equiv \arg\left[ \frac{-V_{ts}^* V_{tb}^*}{V_{cs}^* V_{cb}^*} \right]\]

\( \phi_s^{c\bar{c}s} = -2\beta_s \)
Time dependent CP violation: \( \phi_s^{c \bar{c}s} \)

New LHCb measurement with Run2

\[
\phi_s^{c \bar{c}s} = (-0.039 \pm 0.022 \pm 0.006) \text{ rad}
\]

Results in agreements with SM prediction but still room for New Physics!
Time dependent CP violation: \( \phi_s^{S \bar{S} S} \)

Time dependent CP violation in \( B_s^0 \to \phi \phi \) characterized by \( \phi_s^{S \bar{S} S} \) and \(|\lambda|\) parameters.

Final state produced in three linear polarization states \( \to \) polarization-(in)dependent measurement.

\[ \phi_{s,0} = -0.18 \pm 0.09 \text{ rad} \]
\[ \phi_{s,\|} - \phi_{s,0} = 0.12 \pm 0.09 \text{ rad} \]
\[ \phi_{s,\perp} - \phi_{s,0} = 0.17 \pm 0.09 \text{ rad} \]

First polarization-dependent measurement.

Run1+2 combination

\[ \phi_s^{S \bar{S} S} = (-0.074 \pm 0.069) \text{ rad} \]
\[ |\lambda| = 1.009 \pm 0.030 \]

Most precise measurement of time-dependent CP asymmetry in any penguin-dominated B meson decay.

Important for future precision measurements.
Hadron Spectroscopy: new baryons in $\Xi^{-}_b\pi^+\pi^-$ and $\Xi^{0}_b\pi^+\pi^-$

72 hadrons (49 conventional + 23 exotic) have been discovered at the LHC, of which 64 by LHCb.

Important to develop a deeper understanding of QCD.

Confirmed states:
- $\Xi^{-}_b(6100)$
- $\Xi^{0}_b(6087)$

First observations:
- $\Xi^{-}_b(6095)$

Fully hadronic decay chain $\rightarrow$ up to 9 tracks in the final state.

LHCb-PAPER-2023-008 in preparation
**EW measurements: Z boson production**

**Z boson production cross section in pp collisions @ $\sqrt{s_{\text{NN}}} = 5.02$ TeV (100 pb$^{-1}$)**

$LHCb$ provides EW measurements in forward direction complementary to ATLAS and CMS

**$Z \to \mu^+\mu^-$**

- $2.0 < \eta_\mu < 4.5$
- $p_T^\mu > 20$ GeV/c
- $60 < M_{\mu\mu} < 120$ GeV/c$^2$

**Integrated cross sections**

- \[
\sigma_{Z/\gamma^* \to \mu\mu} = 39.6 \pm 0.7 \pm 0.6 \pm 0.8 \text{ pb}
\]

**Nuclear modification factors**

- \[
R_{pPb}^F = 1.16^{+0.46}_{-0.34} \text{ (stat)} \pm 0.11 \text{ (syst)}
\]
- \[
R_{pPb}^B = 3.64^{+1.55}_{-0.94} \text{ (stat)} \pm 0.20 \text{ (syst)}
\]
Production of $D^+$ and $D_s^+$ mesons in pPb @ $\sqrt{s_{NN}} = 5.02$ TeV, corresponding to $1.58 \pm 0.02$ nb$^{-1}$

**Differential production cross section**

$$\frac{d^2\sigma}{d p_T dy^*} = \mathcal{L} \times \varepsilon_{\text{tot}} \times B \times \Delta p_T \times \Delta y^*$$

First measurement in $1.5 < y^* < 4.0$ and $-5.0 < y^* < -2.5$ down to zero transverse momentum

$y^*$ = rapidity of candidates in the NN centre–of–mass

**Cross section ratios**

Ratio consistent with pp @ LHCb and ALICE mid-rapidity

**Nuclear modification factors**

Suppression in the forward region, consistent among different D mesons
Fully exploit the HL–LHC for flavour physics

\[ L_{\text{peak}} = 1.5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1} \]
\[ L_{\text{int}} \approx 300 \text{ fb}^{-1} \text{ during Run 5+6} \]

➢ Framework TDR approved March 2022
   [CERN–LHCC–2021–012]

➢ Scoping document in preparation for 2024

➢ Limited-size detector consolidations also proposed for LS3,
  needed to ensure to keep on the time for Upgrade II
  • Technical Design Report for PID (RICH/ECAL) in preparation
Summary

✔ LHCb U1 installation is complete
✔ Sub-detectors, trigger and data flow commissioning is advancing
✔ A lot of effort to study the early data from Run3:
  ➢ demonstrated the improved detector performance
  ➢ demonstrated performance of the fully software trigger

LHCb has a broad physics program and it continues to exploit the Run1+2 data set making important measurements

\[
S_{\psi K_s}^{Run2} = \sin 2\beta = 0.716 \pm 0.013_{stat} \pm 0.008_{syst}
\]

\[
\phi_s^{c\bar{c}s} = (-0.039 \pm 0.022 \pm 0.006) \text{ rad} \quad \phi_s^{s\bar{s}s} = (-0.074 \pm 0.069) \text{ rad}
\]

Most precise results in benchmark measurements to search for New Physics!

CERN–LHC Seminar on 13 June

Huge thanks to the LHC for their support!
2023 data @ 6.8 TeV

Thanks for your attention