LHCb Status Report

Preema Pais
EPFL
On behalf of the LHCb Collaboration

LHCC open session
September 12, 2018
CERN
To date, a total of 8.8 fb\(^{-1}\) has been recorded

✦ 1.80 fb\(^{-1}\) collected (so far) in 2018
✦ Thanks to the LHC for excellent machine availability!
• Cumulative data-taking efficiency increasing, approaching 90%
• Alignment and calibration of the detector performed in real-time
Higher luminosity dataset → new analyses, increasing in complexity

High demand for MC simulation

- Current production rate at ~25 million events per day

Need to innovate to keep up with demand

- HLT farm used to produce MC simulated samples whenever possible (26.5% of total production)
- Increasing number of analyses adopting faster simulation techniques
Physics Analysis

- 447 papers in total
  - 19 papers (+ 1 CONF note) submitted for publication since the last LHCC session
- Three analyses with preliminary results
- Additional 32 analyses in review
<table>
<thead>
<tr>
<th>Paper Number</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>PAPER-2018-021</td>
<td>Prompt $\Lambda^+<em>c$ production in pPb collisions at $\sqrt{s</em>{NN}}=5.02$ TeV</td>
</tr>
<tr>
<td>PAPER-2018-030</td>
<td>Search for lepton-flavour-violating decays of Higgs-like bosons</td>
</tr>
<tr>
<td>PAPER-2018-031</td>
<td>Measurement of antiproton production in pHe collisions at $\sqrt{s_{NN}}=110$ GeV</td>
</tr>
<tr>
<td>PAPER-2018-029</td>
<td>Angular moments of the decay $\Lambda^0_b \rightarrow \Lambda \mu^+\mu^-$ at low hadronic recoil</td>
</tr>
<tr>
<td>PAPER-2018-025</td>
<td>Search for CP violation in $\Lambda^0_b \rightarrow pK^-$ and $\Lambda^0_b \rightarrow p\pi^-$ decays</td>
</tr>
<tr>
<td>PAPER-2018-024</td>
<td>Measurement of the relative $B^- \rightarrow D^0/D'^0/D^{*0}\mu^+\bar{\nu}_\mu$ branching fractions using $B^-$ mesons from $B^{*0s}$ decays</td>
</tr>
<tr>
<td>PAPER-2018-028</td>
<td>Measurement of the $\Omega^0_c$ baryon lifetime</td>
</tr>
<tr>
<td>PAPER-2018-026</td>
<td>First observation of the doubly charmed baryon decay $\Xi_{cc}^{++} \rightarrow \Xi_c^{*+}\pi^+$</td>
</tr>
<tr>
<td>PAPER-2018-015</td>
<td>Observation of $B^{0_s} \rightarrow D*\phi$ and search for $B^0 \rightarrow D^0\phi$ decays</td>
</tr>
<tr>
<td>PAPER-2018-014</td>
<td>Observation of the decay $B^{0_s} \rightarrow \bar{D}^0 K^+ K^-$</td>
</tr>
<tr>
<td>PAPER-2018-020</td>
<td>Measurement of angular and CP asymmetries in $D^0 \rightarrow \pi^+\pi^-\mu^+\mu^-$ and $D^0 \rightarrow K^+K^-\mu^+\mu^-$ decays</td>
</tr>
<tr>
<td>PAPER-2018-018</td>
<td>Observation of the decay $\bar{D}^{0_s} \rightarrow \chi_{2c} K^+ K^-$</td>
</tr>
<tr>
<td>PAPER-2018-027</td>
<td>Search for beautiful tetraquarks in the $\Upsilon(1S)\mu^+\mu^-$ invariant-mass spectrum</td>
</tr>
<tr>
<td>PAPER-2018-022</td>
<td>Observation of the decay $\Lambda^0_b \rightarrow \psi(2S)\rho\pi^-$</td>
</tr>
<tr>
<td>PAPER-2018-016</td>
<td>Measurement of $Z \rightarrow \tau^+\tau^-$ production in proton-proton collisions at $\sqrt{s}=8$ TeV</td>
</tr>
<tr>
<td>PAPER-2018-011</td>
<td>Central exclusive production of $J/\psi$ and $\psi(2S)$ mesons in pp collisions at $\sqrt{s}=13$ TeV</td>
</tr>
<tr>
<td>PAPER-2018-019</td>
<td>First measurement of the lifetime of the doubly charmed baryon $\Xi_{cc}^{++}$</td>
</tr>
<tr>
<td>PAPER-2018-012</td>
<td>Measurement of the time-integrated CP asymmetry in $D^0 \rightarrow K^0_s K^0_s$ decays</td>
</tr>
<tr>
<td>PAPER-2018-017</td>
<td>Measurement of the CKM angle $\gamma$ using $B^+ \rightarrow D K^+$ with $D \rightarrow K^0_s \pi^+\pi^-$, $K^0_s K^+K^-$ decays</td>
</tr>
<tr>
<td>PAPER-2018-032</td>
<td>Observation of two resonances in the $\Lambda^0_b \pi^{\pm}$ systems and precise measurement of the $\Sigma_{b}^{\pm}$ and $\Sigma_{b}^{*\pm}$ properties</td>
</tr>
<tr>
<td>PAPER-2018-033</td>
<td>Measurement of the branching ratios of the decays $D^+ \rightarrow K^+K^+K^+$, $D^+ \rightarrow \pi^+\pi^+K^+$ and $D^{*+} \rightarrow \pi^+K^+K^+$</td>
</tr>
<tr>
<td>PAPER-2018-034</td>
<td>Evidence for a $\eta_c(1S)\pi^-$ resonance in $B^0 \rightarrow \eta_c(1S)K^+\pi^-$ decays</td>
</tr>
</tbody>
</table>
**First Observation of the Decay** $\Xi_{cc}^{++} \rightarrow \Sigma_c^{+}\pi^+$

- $\Xi_{cc}^{++} \rightarrow \Lambda_c^{+}K^{-}\pi^{+}\pi^{+}$ decay first observed by LHCb (PRL 119, 112001)
- Lifetime study of decay via weak interaction
- $\Xi_{cc}^{++} \rightarrow \Xi_c^{+}\pi^{+}$ decays expected to have a sizable branching fraction
- Search performed with 1.7 fb$^{-1}$ of data at $\sqrt{s}=13$ TeV
- Events selected with $\Xi_c^{+} \rightarrow pK^{-}\pi^{+}$
- $\Xi_{cc}^{++} \rightarrow \Lambda_c^{+}K^{-}\pi^{+}\pi^{+}$ used as a control channel

$\Xi_{cc}^{++}$ mass consistent with previous measurement:

\[3620.6 \pm 1.5 \text{ (stat)} \pm 0.4 \text{ (syst)} \text{ MeV/c}^2\]

- Branching fraction ratio with respect to previous measurement:

\[0.035 \pm 0.009 \text{ (stat)} \pm 0.003 \text{ (syst)}\]
MEASUREMENT OF THE $\Omega_c^0$ BARYON LIFETIME

- c-baryon lifetime measurement useful for testing higher order effects in heavy quark expansion (HQE)

- Lifetime measurement performed with $\Omega_c^0 \rightarrow pK\pi\pi$ decays obtained from $\Omega_b^0 \rightarrow \Omega_c^0 \mu^-\nu X$ using 3 fb$^{-1}$ of data (Run 1)

- $B^+ \rightarrow D^+ \mu^-\nu X$ decays used as a normalization channel

- Invariant mass fit performed with signal modelled using a double gaussian

---

![LHCB-Graph1](image1)

$+$ Data

- Full fit

$\Omega_c^0 \rightarrow pK\pi\pi$ Comb.

---

![LHCB-Graph2](image2)

$+$ Data

- Full fit

$D^+ \rightarrow K^-\pi^+\pi^+$ Comb.
• Simultaneous fit to $\Omega_c^0$ and $D^+$ decay time distributions

$$\tau_{\Omega_c^0} \over \tau_{D^+} = 0.258 \pm 0.023 \pm 0.010$$

$$\tau_{\Omega_c^0} = 268 \pm 24 \pm 10 \pm 2 \text{ fs},$$

• Results obtained inconsistent with PDG averages, change expected mass hierarchy:

$$\tau_{\Xi^+} > \tau_{\Omega_c^0} > \tau_{\Lambda_c^+} > \tau_{\Xi_c^0}$$

LHCb

**Measurement of the $\Omega_c^0$ Baryon Lifetime**

LHCb-PAPER-2018-028

![Graph showing $\Omega_c^0$ decay time distributions with data and fit]

![Graph showing $D^+$ decay time distributions with data and fit]
OBSERVATION OF TWO RESONANCES IN THE $\Lambda^0_b\pi^\pm$ SYSTEMS

- Study of the $\Lambda^0_b\pi^\pm$ system using reconstructed $\Lambda^0_b$ ($\rightarrow \Lambda_c^{+}\pi^{-}$) baryons combined with a prompt pion
  - Uses a dataset of 3 fb$^{-1}$
  - 234,270 ± 900 $\Lambda^0_b$ candidates, those within 50 MeV/c$^2$ of the peak maximum combined with a prompt pion
- First study data with prompt pion $p_T > 200$ MeV/c$^2$ and $Q = m(\Lambda^0_b\pi^\pm) - m(\Lambda^0_b) - m(\pi^\pm) < 200$ MeV/c$^2$
  - Improved measurement of ground state $\Sigma^\pm$ and $\Sigma^{\ast\pm}$ baryon properties
  - Results consistent with previous CDF measurements, precision improved by a factor 5
Observation of two resonances in the $\Lambda^0_b\pi^\pm$ systems

- Extend study to region with $Q < 600$ MeV/c$^2$
- Higher prompt pion $p_T$ requirement ($> 1000$ MeV/c$^2$) needed to suppress combinatorial background
- Peaks with local significances of $12.7\sigma$ (12.6 $\sigma$) are seen in the $\Lambda^0_b\pi^+$($\Lambda^0_b\pi^-$) distributions
Evidence for a $\eta_c(1S)\pi^-$ resonance in $B^0\rightarrow\eta_c(1S)K^+\pi^-$ decays

- Two-dimensional amplitude analysis of $B^0\rightarrow\eta_c(1S)K^+\pi^-$ decays performed with 4.7 fb$^{-1}$ of data
- Studies the $\bar{p}pK^+\pi^-$ spectrum, search for exotic $\eta_c\pi^-$ or $\eta_cK^+$ states (where $\eta_c$ is reconstructed from a $\bar{p}p$ final state)
- Isobar model used to build amplitude description
- Coherent sum of amplitudes from resonant and non-resonant intermediate states
• Compare baseline model including only $K^*$ resonances to models with additional amplitudes
• Good agreement with data is found when including a charged charmonium-like resonance
  • $3\sigma$ significance for $Z_c(4100)^-$
  • Cannot discriminate between favoured spin parity states $J^P=0^+$ and $1^-$
• Additional statistics available with full Run 2 dataset (and in future datasets) will enable further study
**Antiproton Production in pHe Collisions at $\sqrt{s_{NN}} = 110$ GeV**

- Antiproton fraction in cosmic rays sensitive indirect probe of exotic astrophysical sources of antimatter
- Precision measurements of antiproton-proton flux ratio from PAMELA, AMS
  - Uncertainties in 10-100 GeV antiproton energy range dominated by uncertainty on production cross-section
- First measurement of prompt antiproton production in pHe collisions
  - Use proton beam of 6.5 TeV on helium gas target
  - PID from RICH detector response
  - 3 templates built from simulated samples
  - 2-d binned extended ML fit and cut-and-count method used to determine antiproton fraction

---

**Graphs and Plots**

1. **LHCb Data**
   - pHe $\sqrt{s_{NN}} = 110$ GeV
   - Various particle distributions
   - PID from RICH detector response

2. **Candidates per $\pi$**
   - Data
   - $\pi^-$, $\bar{p}$, $K^-$
   - $1.2 < p_T < 1.5$ GeV/c, $21.4 < p < 24.4$ GeV/c
   - LHCb $\sqrt{s_{NN}} = 110$ GeV
Antiproton production cross section shown (integrated over different kinematic regions)

• Uncertainty lower than 10% for most bins

• Lower than spread between predictions from various theoretical models

• Improves the precision of secondary antiproton cosmic ray flux predictions
**Angular Moments of the Decay $Λ_0^b → Λμ^+μ^-$**

- $b → s$ transitions proceed via FCNC; forbidden at tree level in the SM
  - New Physics contributions can occur at loop level
- $Λ_b → Λμ^-μ^+$ decay system described by five angles
- Moments analysis performed in the di-muon invariant mass squared range $15 < q^2 < 20$ GeV$^2$/c$^4$ (34 free parameters)
- Analysis performed with 5 fb$^{-1}$ of data (2011, 2012, 2016)
- Forward-backward asymmetries consistent with SM predictions

\[ A^\ell_{FB} = -0.39 \pm 0.04 \text{ (stat)} \pm 0.01 \text{ (syst)} \]
\[ A^h_{FB} = -0.30 \pm 0.05 \text{ (stat)} \pm 0.02 \text{ (syst)} \]
\[ A^{ℓh}_{FB} = +0.25 \pm 0.04 \text{ (stat)} \pm 0.01 \text{ (syst)} \]
• Study of $B^0_s \rightarrow \bar{D}^{(*)0}\phi$ decays could help improve precision on CKM angle $\gamma$

• Measurement of fraction of longitudinal polarisation ($f_L$) could help constrain QCD models, search for NP

• Unbinned maximum likelihood fit of $\bar{D}^{(*)0}KK$ invariant mass spectrum

• $B^0_s \rightarrow \bar{D}^{(*)0}\phi$ signal modelled by non-parametric PDFs from simulated sample

• Two polarizations considered: $f_L=1$ (longitudinal) and $f_L=0$ (transverse)

• Branching fractions measured relative to $\bar{D}^{(*)0}\pi\pi$ decays

• $f_L$ consistent with measurements from other colour-suppressed $B^0$ decays

• Limit set on branching fraction at 90(95)% CL

$$f_L = (73 \pm 15 \pm 3)\%$$

$$\mathcal{B}(B^0 \rightarrow D^0\phi) < 2.0 \ (2.2) \times 10^{-6}$$
### LHCb Upgrade I

<table>
<thead>
<tr>
<th>Year</th>
<th>Run 2</th>
<th>LS2</th>
<th>Run 3</th>
<th>LS3</th>
<th>Run 4</th>
<th>LS4</th>
<th>Run 5,6,...</th>
</tr>
</thead>
<tbody>
<tr>
<td>2015</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2016</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2017</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2018</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2019</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2020</td>
<td>Run 2</td>
<td>LS2</td>
<td>Run 3</td>
<td>LS3</td>
<td>Run 4</td>
<td>LS4</td>
<td>Run 5,6,...</td>
</tr>
<tr>
<td>2021</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2022</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2023</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2024</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2025</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2026</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2027</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2028</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2029</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2030</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2031</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2032</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2033</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **Primary challenges after LS2:**
  - Take advantage of higher luminosity (current L0 hardware trigger limits data-taking rate)
  - Sub-detectors will need to handle increased occupancy (factor 5 increase in number of interactions per bunch crossing)
  - Radiation damage also a concern

\[
L = 4 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}
\]

\~1.1 interactions per bunch crossing

\~9.5 fb\(^{-1}\) expected (2011-2018)

\[
L = 1-2 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}
\]

\~5 interactions per bunch crossing

\~50 fb\(^{-1}\) expected (Runs 3-4)

\[
L = 1-2 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}
\]
LHCb Upgrade I

Software-only trigger

New tracking stations

Upgraded calorimetry FE electronics, remove SPD/PS

Upgraded muon FE electronics, remove M1

New pixel VELO

Si strip tracker

New RICH PMTs + upgraded electronics
LHCb Upgrade I

- Software-only trigger
- New tracking
- Upgraded muon FE electronics, remove M1
- Upgraded calo
- New pixel VELO
- New RICH PMTs + upgraded electronics
- To be UPGRADED
- To be kept
- Detector Channels
- R/O Electronics
- DAQ
UNIT IGRADE I HIGHLIGHTS

VELO

- Module production PRR passed on July 16
  - Final prototype modules being constructed
  - Preparing for site-specific review
- Sensor and VeloPix ASICs production complete
- Tile production + testing well underway

Upstream Tracker

- Received first series of A-type sensors
- Bare stave production almost complete
- PEPI electronics PRR passed, ready for production
- Delays with SALT ASIC, aim for v3 submission at the end of this month
- Significant progress on integration & cooling
**Upgrade I Highlights**

**SciFi tracker**
- Fibre mat production essentially complete
- >90% of modules produced
- C-frame production to begin soon
- Successful test beam in July, validation of full readout chain

**RICH detectors**
- MaPMT production and QA completed
- Several developments (DAQ, controls) from system tests carried out at SysLab@CERN
- Electronics and mechanics production well underway
Computing Model TDR

- Document describing offline computing model for LHCb from Run 3 onwards, and related computing resource needs
  - First draft of TDR in preparation
    - Details baseline scenario for resource needs plus potential alternative models
  - General model considerations:
    - CPU resources dominated by MC production
    - Majority of data processing done via TURBO, with substantial data volume reduction
  - Alternative models include:
    - data parking to mitigate disk usage
    - increased development of faster simulation methods to reduce CPU needs
  - Aim to submit document to LHCC by end-September

Table of contents

1 Introduction and Scope
2 Historical evolution of the computing model during LHC Run 1 and Run 2
3 Evolution of the Physics Case
4 Run 3 Logical Workflows
   4.1 Offline Data Handling
   4.2 User Analysis
   4.3 Simulation
5 Resource Provisioning
   5.1 Computing Infrastructure Requirements
   5.2 Pledged Computing Resources via WLCG
   5.3 Non Pledged Computing Resources
6 Resource Requirements
   6.1 Baseline scenario
   6.2. Data Parking
   6.3. Reduced HLT Output Bandwidth
   6.4 Combined Data Parking and Reduced HLT Output Bandwidth
   6.5 Aggressive Fast Simulation Development
7 Bibliography
In HL-LHC environment, expect factor 10 increase in luminosity, interactions per bunch crossing

- Aim at exploiting HL-LHC phase to collect >300 fb⁻¹

- Huge challenge for detectors and TDAQ system

- Submitted Upgrade II Expression of Interest (EoI) in 2017

- New physics case document submitted to arXiv on August 27
## LHCb Upgrade II


<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><strong>EW Penguins</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R_K$ ($1 &lt; q^2 &lt; 6 \text{ GeV}^2c^4$)</td>
<td>0.1</td>
<td>0.025</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>
<tr>
<td><strong>CKM tests</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\gamma$, with $B^0_s \rightarrow D_s^+K^-$</td>
<td>4$^\circ$</td>
<td>–</td>
<td>1$^\circ$</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>$\gamma$, all modes</td>
<td>$^{(+17)\circ}_{(-22)^\circ}$</td>
<td>1.5$^\circ$</td>
<td>1.5$^\circ$</td>
<td>0.35$^\circ$</td>
<td>–</td>
</tr>
<tr>
<td>sin $2\beta$, with $B^0 \rightarrow J/\psi K^0$</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 $B^0_s \rightarrow J/\psi\phi$</td>
<td>49 mrad</td>
<td>14 mrad</td>
<td>–</td>
<td>4 mrad</td>
<td>22 mrad</td>
</tr>
<tr>
<td>$\phi_s$, with $B^0_s \rightarrow D_s^+D_s^-$</td>
<td>170 mrad</td>
<td>35 mrad</td>
<td>–</td>
<td>9 mrad</td>
<td>–</td>
</tr>
<tr>
<td>$\phi_s^{ss}$, with $B^0_s \rightarrow \phi\phi$</td>
<td>154 mrad</td>
<td>39 mrad</td>
<td>–</td>
<td>11 mrad</td>
<td>Under study</td>
</tr>
<tr>
<td>$q_s$</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>$</td>
<td></td>
<td>V_{ub}</td>
<td></td>
<td>/</td>
<td></td>
</tr>
<tr>
<td>$B^0_s$, $B^0 \rightarrow \mu^+\mu^-$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\frac{B(B^0 \rightarrow \mu^+\mu^-)/B(B^0_s \rightarrow \mu^+\mu^-)}{}$</td>
<td>90%</td>
<td>34%</td>
<td>–</td>
<td>10%</td>
<td>21%</td>
</tr>
<tr>
<td>$\tau_{B^0_s \rightarrow \mu^+\mu^-$</td>
<td>22%</td>
<td>8%</td>
<td>–</td>
<td>2%</td>
<td>–</td>
</tr>
<tr>
<td>$S_{\mu\mu}$</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>0.2</td>
</tr>
<tr>
<td><strong>$b \rightarrow c\ell^-\bar{\nu}_l$ LUV studies</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R(D^*)$</td>
<td>0.026</td>
<td>0.0072</td>
<td>0.005</td>
<td>0.002</td>
<td>–</td>
</tr>
<tr>
<td>$R(J/\psi)$</td>
<td>0.24</td>
<td>0.071</td>
<td>–</td>
<td>0.02</td>
<td>–</td>
</tr>
<tr>
<td><strong>Charm</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<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>$A_{\tau}$ ($\approx x \sin \phi$)</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>$(K3\pi)$ $4.0 \times 10^{-5}$</td>
<td>$(K_{s0}^0\pi\pi)$ $1.2 \times 10^{-4}$</td>
<td>$(K3\pi)$ $8.0 \times 10^{-6}$</td>
<td>–</td>
</tr>
</tbody>
</table>
Increased sensitivity to unitarity triangle parameters
Can assess tree-level observables against (NP-sensitive) loop-level contributions

**CKM tests**

- $\gamma$, with $B_s^0 \to D_s^+ K^-$
  - $(+17)_o$
  - $(-5.8)_o$

- $\gamma$, all modes
  - $4^o$
  - $1.5^o$
  - $1.5^o$
  - $0.35^o$

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

**Charm**

- $\Delta A_{CP}(K K - \pi\pi)$
  - $8.5 \times 10^{-4}$
  - $1.7 \times 10^{-4}$
  - $5.4 \times 10^{-4}$
  - $3.0 \times 10^{-5}$

- $A_T (~ x \sin \phi)$
  - $2.8 \times 10^{-4}$
  - $4.3 \times 10^{-5}$
  - $3.5 \times 10^{-4}$
  - $1.0 \times 10^{-5}$

- $x \sin \phi$ from $D^0 \to K^+ \pi^-$
  - $13 \times 10^{-4}$
  - $3.2 \times 10^{-4}$
  - $4.6 \times 10^{-4}$
  - $8.0 \times 10^{-5}$

- $x \sin \phi$ from multibody decays
  - $(K^0 \pi \pi)$ $4.0 \times 10^{-5}$
  - $(K^0_\pi \pi \pi)$ $1.2 \times 10^{-4}$
  - $(K_\pi \pi)$ $8.0 \times 10^{-6}$
LHCb Upgrade II

Reach of Upgrade II factor ~2 higher than Upgrade I
Sensitivity up to $\Lambda_{NP} = 100$ TeV

Includes K*ll angular analyses
SUMMARY

- LHCb operating well in the final few months of data-taking in Run 2
  - New and more complex analyses constantly being added to physics program
- Preparation for LHCb upgrade I proceeding well
  - LS2 dismantling/installation workshop held in May, schedule in place
  - First draft of computing model TDR circulated
  - Multi-system test beam planned for October
- LHCb Upgrade II will ~double the new physics scale probed compared to pre HL-LHC
  - Widen the set of observables under study to search for and characterise new physics
  - Strong programme beyond flavour exploiting unique acceptance
- Physics case document submitted on August 27
BACKUP
Several cross-checks performed:

- s-weighted distributions for $\Omega_c^0 \mu^-$ mass, pT decay time compared with data to check selection of semi-leptonic $\Omega_b^0$ decays; good agreement found.
- Lifetime measurement performed with $\Omega_c^0$ mass sideband subtraction, good agreement with result obtained from sPlot method.
- Lifetime study with independent sample of $\Omega_c^0$ decays collected at 13 TeV center-of-mass energy performed, result consistent with this analysis.
- Method also used to measure $D^0$ meson lifetime from a sample of $\sim 88,000$ $B \rightarrow D^0(\rightarrow K^+K^-\mu^+\mu^-)\mu X$ decays; result consistent
- Consistent values obtained with with tighter BDT selection criteria or tighter PID requirements.
Trigger system:

Initial hardware trigger (L0), using information from calorimeters and muon system.

Software trigger split into two stages: fast partial event reconstruction + subsequent full reco.

Low luminosity → can trigger on relatively low pT objects.
• Software-only trigger in the upgrade
  • Current L0 hardware trigger to be removed
• Must fully process events at 30 MHz
  • Information needed from all sub-detectors at initial trigger stage
• Events stored in buffer, for online alignment, calibration
  • Will be able to trigger on signatures with large impact parameters, high $p_T$
• Event sized reduced to write to disk at 2-5 Gb/s
VELO challenges in Run 3:
- Retain high vertex and track reco. efficiency with ~ 5x increase in interactions per bunch crossing
- Increased radiation (order of magnitude higher than current doses), highly non-uniform

- Use silicon hybrid pixels
- 52 modules, two retractable halves
  - Innermost sections ~5.1 mm from beam pipe
  - 4 silicon sensors per module, 55 μm x 55 μm
UPGRADE I - VELO

• Pixel VELO ASIC front-end readout chip
  • 3 chips bump-bonded to each sensor

• Sensor+readout electronics mounted on cooling substrate
  • Sensor temperature maintained at -20 C, novel technique of evaporated CO$_2$ cooling in substrate micro-channels
  • Minimal material within acceptance

• VELO separated from primary vacuum by 1.1 m long thin RF foil
  • New foil thinned to 250 µm
  • Withstands pressure variations of 10 mbar
Upgrade I - UT

- Four-layer silicon strip detector
  - Finer granularity, innermost sensors closer to beam pipe
  - Inner layers tilted by a stereo angle (±5%)
- Four different types of sensors
- Mounted to lightweight staves (10 cm wide, 1.6 m long)
- Novel readout chip (SALT ASIC)
Upgrade I - SciFi

- 3 x 4 layers of scintillating fiber mats
- Each mat with 6 layers of fibres
- 8 mats assembled into a module
- 11,000 km of fibres in total
- Coverage up to 3m from the beam pipe
- Single photon efficiency ~99%

- Fibres manufactured by Kuraray (Japan)
  - Double-clad plastic scintillating fibre
  - Core: polystyrene base + activator + wavelength shifting dye
  - Attenuation length ~ 3.5m, light emissions peak ~ 450 nm
• Fibre QA done at CERN
  • Spools from manufacturer scanned for mechanical defects
  • Bumps above threshold removed with a ‘hot drawing' tool
• Mats assembled with custom winding machine
  • Second fibre QA performed
• Mats aligned within 50 μm over 5 m length using alignment pins
**Fibre readout provided by silicon photo-multipliers**

- 128-channel SiPM arrays, channel size 250 um
- Cooled to -40°C to minimize dark count rate after high irradiation
- Photon detection efficiency ~ 45%
- SiPM signal processed by custom 64-channel PACIFIC ASIC chip
- Zero suppression + clustering on FPGAs (clusterisation boards)
• New glass flat mirrors for RICH1 (better photon yield)
  • Focal plane, optics modified to increase size of Cherenkov rings
• Photo-detectors to be upgraded
  • Two types of multi-anode photomultiplier tubes (MaPMTs) with finer granularity
• Readout electronics updated to allow for data-taking at 40 MHz
• Single photon angular resolution improved by 50% (RICH1), 20% (RICH2)
Upgrade I - Calo+Muon

- Current calorimeters will be kept for Run 3
  - Front-end electronics rebuilt
  - SPD/PS removed
- PMT gain reduced by a factor of 5 to reduce degradation
- To compensate, the front-end gain is increased by the same factor
  - Custom low-noise FE ASIC developed
- Reconstruction improved for higher occupancy environment
- Muon detector electronics also upgraded during LS2
  - First GEM layer to be removed
  - 36 new PAD chambers to be installed in inner region