Status of LHCb Upgrade I

- Collaboration matters
- Run 1 + Run 2 summary
- Physics output and selected physics results
- The LHCb upgrade
- Conclusions and outlook

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INFN – Florence and CERN
On behalf of the LHCb collaboration
RRB – 30/10/2019
The collaboration keeps growing

- Peking University (Beijing, China) joined as full member
- Valencia IFIC (Valencia, Spain) moved from associate to full member
- Monash University (Melbourne Australia) joined as associate member
Run 1 + Run 2 summary

A lot of physics in our granary
Luminosity 2010-2018: a round 10 fb$^{-1}$...

- Got exactly the target luminosity that was hinted at the times of the Technical Proposal (~1998)!

### Integrated luminosity counters in 2018 [1/pb]

<table>
<thead>
<tr>
<th></th>
<th>Recorded</th>
<th>Delivered</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current Fill</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Annual</td>
<td>2190.9</td>
<td>2456.5</td>
<td>89.2</td>
</tr>
<tr>
<td>Mag DOWN</td>
<td>1055.7</td>
<td>1174.1</td>
<td>89.92</td>
</tr>
<tr>
<td>Mag UP</td>
<td>1133.7</td>
<td>1280.8</td>
<td>88.51</td>
</tr>
<tr>
<td>2010-2018</td>
<td>9227.1</td>
<td>10180.9</td>
<td>90.63</td>
</tr>
</tbody>
</table>

- Including:
  - 0.04 fb$^{-1}$ 2010 and
  - 0.13 fb$^{-1}$ 2017 ($\sqrt{s}$=5TeV)

- Excluding:
  - 0.04 fb$^{-1}$ 2010 and
  - 0.13 fb$^{-1}$ 2017 ($\sqrt{s}$=5TeV)

### Luminosity 2010-2018

- 2010 (6.5 TeV): 2.19 fb
- 2011 (6.5+2.5 TeV): 1.71 fb + 0.10 fb
- 2012 (6.5 TeV): 1.67 fb
- 2013 (6.5 TeV): 0.33 fb
- 2015 (6.5 TeV): 2.08 fb
- 2017 (3.5 TeV): 1.11 fb
- 2010 (3.5 TeV): 0.04 fb
...in a range of running modes!

- Different c.o.m. energies
- Collider mode
- Fixed target mode
- Combined
- p-p, Pb-Pb, p-Pb, p-A, Pb-A (A= He, Ne, Ar)

<table>
<thead>
<tr>
<th>E (Z TeV)</th>
<th>( \sqrt{s_{NN}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>pp</td>
</tr>
<tr>
<td>( \sqrt{s} = 2E )</td>
<td>( \sqrt{s} = 2E_{Te} )</td>
</tr>
<tr>
<td>1.38</td>
<td>2.76</td>
</tr>
<tr>
<td>2.51</td>
<td>5.02</td>
</tr>
<tr>
<td>3.5</td>
<td>7</td>
</tr>
<tr>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td>6.37</td>
<td>13</td>
</tr>
<tr>
<td>6.5</td>
<td>13</td>
</tr>
</tbody>
</table>

- Singer mode
- Fixed target mode
- Combined p-p, Pb-Pb, p-Pb, p-A, Pb-A (A= He, Ne, Ar)
Operations: offline computing

- Intense and complex operation activities during LS2
  - MC productions are using more than 90% of the computing power
  - Using the online farm for MC production: ~35% of the sample.
  - ~85% of MC events produced with fast simulation in the last year
  - Reprocessing campaign of Run1 and Run 2 data ongoing
  - Deploying Upgrade software

<table>
<thead>
<tr>
<th>Data set</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>2018</td>
<td>completed</td>
</tr>
<tr>
<td>2011-2012</td>
<td>completed</td>
</tr>
<tr>
<td>2015-2016</td>
<td>Final validation - Production starting. Production time: ~2 months</td>
</tr>
<tr>
<td>2017</td>
<td>Validation ongoing</td>
</tr>
</tbody>
</table>

Events in last 365 days
- 85% of the events produced with fast simulation
Selected physics results

An overview of recent physics highlights
Physics: paper production

- 496 papers total – 39 in 2019
- +2 Conference Notes
- +20 since Apr ‘19 RRB

- 15 more being processed by Editorial Board
- 31 further under collaboration review, several more under working group review
Physics: paper production

- Analysis of full Run 2 data in full swing!
- Substantially growing number of Run 1+ Run 2 analyses
- Several with full Run 1+ Run 2 dataset
Recent physics highlights

- Many **new results** published this year
- Several already using the full Run 1 + Run 2 data set (9 fb⁻¹)
- Will show only a few of them
Recap on CP violation measurements

- *Observation of CP violation in charm*
- *CP violation in $B_s$*
- *CP violation in baryons?*
Observation of CP violation in charm

- Count how many $D^0$ and anti-$D^0$ decay into $\pi^+\pi^-$ and $K^+K^-$
  - If matter = antimatter the number of the $D^0$ anti-$D^0$ decays should be equal
- For experimental reasons we prefer to measure the difference in matter-anti-matter asymmetry between decays into $\pi^+\pi^-$ and $K^+K^-$: $\Delta A_{CP}$
  - should be exactly zero if matter = antimatter
- Result:

  $$\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4}$$

- A tiny but significant (5.3$\sigma$!) difference from zero!
- Roughly compatible with the SM
- However, theoretical predictions are way more uncertain than data
- Opens a new field of investigation!
New measurement of the $B_s$ mixing phase $\phi_s$

- Measure the phase difference between the two processes
- Precisely determined within the SM:
  \[
  \phi_s^{SM} = (-36.8^{+0.96}_{-0.68}) \text{ mrad (CKMFit)} \\
  \phi_s^{SM} = (-37.0 \pm 1.0) \text{ mrad (UTFit)}
  \]

- VERY sensitive to contributions from new particles beyond the SM
- Very high precision measurement
- Updated measurements with Run 2 data:
  $B_s \rightarrow J/\psi \phi$ and $B_s \rightarrow J/\psi \pi \pi$

- Combining with Run 1 yields
  \[
  \phi_s = (-41 \pm 25) \text{ mrad}
  \]

- HFLAV combined value approaching the sensitivity to observe a non zero value!

30/10/2019

RRB - LHCb

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Have still ~4 fb$^{-1}$ in our pockets!
Search for CP violation in baryons

- So far CP violation observed only in mesons. **No observation yet in baryons**
- Search for CP and P violation in \( \Lambda_b \rightarrow p \pi \pi^+ \pi^- \)
- Look for CP and P violation also in specific regions of the kinematic parameters (“phase-space”)

- No CP violation observed, although hints of deviations at the level of 2.9σ are present
- P violation observed for the first time in b-baryons at 5.5σ level

Results integrated over the full phase-space show no CPV

\[
\begin{align*}
\hat{a}_P^{\text{odd}} &= -3.98 \pm 0.70 \pm 0.17 \\
\hat{a}_{CP}^{\text{odd}} &= -0.70 \pm 0.70 \pm 0.17
\end{align*}
\]
Rare decays

- Recap on lepton flavour universality
- Search for $K_s \rightarrow \mu^+\mu^-$
Tests of lepton flavour universality

- Lepton flavour universality can be checked in several B meson decays involving leptons in the final state

- Two main classes of decays have been studied:
  - Semileptonic $B^0 \rightarrow D^{(*)} l^- \nu$ - tree level decay
  - $b \rightarrow s l^+ l^-$ decays e.g. $B^0 \rightarrow K^{(*)0} l^+ l^-$ - FCNC decays

- Observables:
  - $R(D^*) = \frac{BF(B \rightarrow D^* \tau \nu)}{BF(B \rightarrow D^* \mu \nu)} \equiv 0.252 \pm 0.003$

  - $R(K^{(*)}) = \frac{BF(B \rightarrow K^{(*)} \mu^+ \mu^-)}{BF(B \rightarrow K^{(*)} e^+ e^-)} \stackrel{\text{SM}}{\approx} 1$

- Theoretically clean!
Tests of lepton universality: $R(K)$ and $R(K^*)$

Test the LFU in electroweak penguin decays (e.g. the class of FCNC decays $b \to s l^+ l^-$)

- **Old results for $R(K)$ and $R(K^*)$ (Run 1 only):**


$\sim 2-2.5 \sigma$ away from SM
Tests of lepton universality: new measurement of $R(K)$

- New measurement re-analysing Run 1 data and adding $\sim 2 \text{ fb}^{-1}$ of Run 2 data

$$R_K = 0.846^{+0.060}_{-0.054}(\text{stat})^{+0.016}_{-0.014}(\text{syst})$$

- Situation essentially unchanged: still $2.5\sigma$ away from the SM prediction
  - Better precision but central value closer to the SM

- Need more data: inclusion of 2017+2018 data will double the statistics

- Other measurements in preparation
  - Update of $R(K^*)$, other decay channels (e.g. $\Lambda_b \to pK\pi\nu\bar{\nu}$ aka $R(pK)$ )
Search for $K_S \rightarrow \mu^+\mu^-$

- Strongly suppressed FCNC transition – can be enhanced by NP

- New measurement using Run 2 data set
- Extremely rare decay – background suppression challenging
  ★ Dominant source $K_S \rightarrow \pi^+ \pi^-$
  ★ need to strongly suppress secondary vertices from material interaction

Tomography of VELO provides a map to reject background
Search for $K_s \rightarrow \mu^+\mu^-$

- Limit from Run2 data: $2.6 \times 10^{-10} @ 95\%$ CL
- Can combine with Run1 result, limit improves to: $2.4 \times 10^{-10} @ 95\%$ CL
- Limit improved by factor of four w.r.t. previous (LHCb Run1)
- Scope to do much better with the upgrade!
- Could greatly benefit from new all-software trigger.

LHCb preliminary
Run 2, 5.6 fb$^{-1}$
Lifetime measurements

- Measurement of charm baryon lifetimes
Charm baryon lifetimes

- New measurement of $\Lambda_c^+$, $\Xi_c^+$ and $\Xi_c^0$ lifetimes
- Baryons selected from semileptonic $b$-baryon decays
- Measured relative to the $D^+$ lifetime
- Large samples!

<table>
<thead>
<tr>
<th>$H_c$</th>
<th>Yield ($10^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^+$</td>
<td>809.4 ± 1.3</td>
</tr>
<tr>
<td>$\Lambda_c^+$</td>
<td>303.5 ± 0.7</td>
</tr>
<tr>
<td>$\Xi_c^+$</td>
<td>55.8 ± 0.5</td>
</tr>
<tr>
<td>$\Xi_c^0$</td>
<td>21.6 ± 0.2</td>
</tr>
</tbody>
</table>

- Better precision by x3-4 wrt World Average
- Lifetime of $\Xi_c^0$ 3.3σ larger than WA

[Phys. Rev. D100 (2019) 032001, Run1 3.0 fb$^{-1}$]
Upgrade

*Moving towards Run 3*
LHCb Upgrade I in a snapshot

All sub-detectors read out at 40 MHz for a **fully software trigger**

- **Upgraded detector**
  - New silicon upstream tracker (UT)
  - New scintillating fibre tracker (SciFi)
  - New PIXEL vertex detector (VELO)
  - New RICH optics and photodetectors
  - New electronics for muon and calorimeter systems
Upgraded LHCb Detector

Detector Channels

R/O Electronics

To be UPGRADED
To be kept

«This is a new detector at the LHC»
Upgrade: installation

Sorting out infrastructure and services
Very intense activity at LHCb site!

- All old detectors and obsolete equipment removed
- All new cooling systems installed
- All optical fibres in place
- New computing centre in place
- Watch our videos!

~19k optical fibres, 99.8% OK!

New computing center completed

RRB - LHCb
Upgrade: construction

Working full steam
Upgrade: VELO

- Production of VELO modules started, although still not at the nominal pace
- Mechanics and readout electronics progressing well
- Important decision to proceed to RF-foil etching: successfully thinned down to 150 µm
- Tight schedule!

VELO etching with NaOH solution
Green area is passivated
Etched boxes are now at Nikhef for final metrology and coating
• SALT3.5
  ★ 18 wafers received in early July
  ★ Wafer testing completed in summer
  ★ Good yield: ~82 % ⇒ ~6850 chips
• SALT3.8 (8-chip hybrid version): diced chips at CERN, ready for final tests
• Hybrids and flex cables being produced
• Ready to start stave production
• Readout electronics and mechanics progressing well
• Tight schedule!
Upgrade: SciFi

- All components at hand, installing detector stations ("C-Frames")
- Very complex objects, including cooling system at -40°
- 3/12 C-frames well advanced – need to install 6 before beam pipe installation
- Tight schedule!
Upgrade: RICH

- All components for photon detection system at hand
- Readout electronics produced
- Q&A well advanced, components at CERN for "column" assembly
- RICH1 spherical mirrors at CERN for coating
- Mechanics progressing well
- RICH1 MaPMT support chassis and gas enclosure installed.
- **Unfortunately problem: the quartz window cracked**
  - ★ Need to build a new one
  - ★ Essentially no input on schedule but additional work needed
Upgrade: Calorimeters, Muon system

**Muon system**
- All new electronic boards in production
- First boards already at CERN, commissioning already ongoing
- Additional shielding: pieces at CERN, ready for installation

**Calorimeters**
- New front-end ASIC: completed
- HV/Monitoring/calibration boards: completed
- Front-end boards: production delayed
- Control boards: delayed (linked to the above)
- Production completed and installation in February 2020 – may become tight
Upgrade: Online

- Construction of common DAQ boards (PCIe40) progressing well: 68% produced and tested.
- Acceptance test setup running full steam
- Vertical slice to test the whole DAQ chain

- Review of event builder technology held in Jun
  - two alternative technologies being considered, with different network configurations
  - Decision will be taken in December

- Computing centre buildings completed
Upgrade: full software trigger

- Development under the responsibility of the Real-Time Analysis Project (RTA)
- Major break-through in summer: HLT1 throughput >30 MHz
- Very promising physics performance studies
  ★ Fixed target (-> demonstrates full flexibility!)
  ★ Real time alignments
- Development of HLT2 selections started

HLT1 must process 30M events/sec
Upgrade II

*LHCb Upgrade II: the ultimate exploitation of LHC for flavour physics*
Aim to **fully exploit HL-LHC** for flavour physics and other opportunities in the forward direction

- Aim to collect $> 300 \text{ fb}^{-1}$ at $L = 2 \times 10^{34}$, $x10$ with respect to Upgrade I
- Expression of Interest issued in 2017
- Feasibility study performed by LHC experts
- **Physics case document released**
- Support for project in the *Physics Briefing Book : Input for the European Strategy for Particle Physics Update 2020* – “The LHCb Upgrade II... will enable a wide range of flavour observables to be determined at HL-LHC with unprecedented precision”
- Green light from LHCC to proceed to a Framework TDR (expected 2021)
Conclusions and outlook
Conclusions and outlook

- Completed a successful first phase of LHCb
  - We were delivered 10 fb⁻¹ which was the goal in our Technical Proposal in 1998!
  - Collected data in a variety of running conditions

- LHCb continues to provide a wealth of excellent physics results

- The march towards the Upgrade I is continuing
  - All subsystems progressing - installation ongoing!
  - Schedule is tight, working hard to be ready for LHC Run 3!

- Looking into the far future:
  - Expression of Interest for future upgrades submitted
  - Physics case document released
  - Green light from LHCC to proceed to a Framework TDR
  - Clear case also for ESPP
  - A lot of R&D opportunities!
Thank you!
Measurement of CP violation in $B_s \to \phi\phi$

- Decay dominated by a penguin loop: enhanced sensitivity to New Physics
- Measure the phase $\phi_s^{S\bar{S}S}$ analogous to $\phi_s$.
- SM predictions: $|\phi_s^{S\bar{S}S}| < 20$ mrad

- Perform time dependent angular analysis

$$\phi_s^{S\bar{S}S} = -0.073 \pm 0.115 \pm 0.027 \text{ [rad]}$$
$$|\lambda| = -0.99 \pm 0.05 \pm 0.01$$
Lepton flavour violating decay $B^0/B_s \to \tau \mu$

- Search for lepton-flavour violating decays $B^0/B_s \to \tau \mu$
- BR in SM awfully small: $\sim 10^{-54}$
- Can be strongly enhanced in NP models: up to $O(10^{-8} - 10^{-5})$ – link to LFUV models.

- Look for three prong $\tau$ decays

<table>
<thead>
<tr>
<th>Mode</th>
<th>Limit</th>
<th>90% CL</th>
<th>95% CL</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0_s \to \tau^\pm \mu^\mp$</td>
<td>Observed</td>
<td>$3.4 \times 10^{-5}$</td>
<td>$4.2 \times 10^{-5}$</td>
</tr>
<tr>
<td></td>
<td>Expected</td>
<td>$3.9 \times 10^{-5}$</td>
<td>$4.7 \times 10^{-5}$</td>
</tr>
<tr>
<td>$B^0 \to \tau^\pm \mu^\mp$</td>
<td>Observed</td>
<td>$1.2 \times 10^{-5}$</td>
<td>$1.4 \times 10^{-5}$</td>
</tr>
<tr>
<td></td>
<td>Expected</td>
<td>$1.6 \times 10^{-5}$</td>
<td>$1.9 \times 10^{-5}$</td>
</tr>
</tbody>
</table>

First limits
Best limits
New measurement of the $B_s$ mixing phase $\phi_s$

- Combining with Run 1 yields
  - $\phi_s = (-41 \pm 25)$ mrad
  - $|\lambda| = 0.993 \pm 0.010$
  - $\Gamma_s = 0.6562 \pm 0.0021$ ps$^{-1}$
  - $\Delta\Gamma_s = 0.6562 \pm 0.0021$ ps$^{-1}$