LHCb Summary

Michael McCann
on behalf of LHCb

Imperial College London

30 November 2016
128th LHCC meeting: Open Session
Introduction

Busy few months for LHCb, this talk will cover:

- 2016 Operations
  - General improvements
  - $pp$ running
  - $pPb$–$Pbp$ running
  - EYETS

- Physics program
  - Overview
  - Highlights
    - Including new results at CKM

- LS2 upgrade program
New control room and automation

- Purpose built control room
- Pleasure to spend time there
- Dedicated meeting room
- Four coffee machines!

- High levels of automation
- Experiment run by two shifters
- Often only need to accept handshakes
- Backed up by dozens of experts and piquets
HLT (software trigger)

- HLT split into two stages
  - HLT1: Uses basic event info
  - HLT2: Fully calibrated and reconstructed event info
- HLT1 output parked until HLT2 run
  - 10 PB disk buffers available
- HLT2 runs when HLT1 isn’t using full resources
- Tuned adaptively to conditions for maximum efficiency

![Disk usage graph](image)
Detector calibrations run in real time, run-by-run or fill-by-fill

- Run automatically
  - VELO alignment
  - Tracker alignments
  - Muon alignments
  - RICH gas calibrations
  & mirror alignments
- Update only if needed
- Ready before HLT2 runs
LHC 2016 $pp$ program now complete

Very successful period for LHCb

- 1.7 fb$^{-1}$ taken
- Including 2015 1.99 fb$^{-1}$ total, equal to 2012 but much higher cross-sections $\sim \times 2b\bar{b}$

Luminosity levelling to $\mu \sim 1.1$ effective

Thanks to LHC for excellent running

Av. rec. lumi. = 0.3 nb$^{-1}$s$^{-1}$, better with more bunches
Excellent online charm reconstruction and yields

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

\[ m(D^{*+}) - m(D^0) \text{ [MeV}/c^2] \]

- **K\(_S^0\) vtx inside VELO**
  - \( N_D \approx 3.2 \times 10^6 \) (1.6M/fb)
  - Run1: 0.3M/fb

- **K\(_S^0\) vtx outside VELO**
  - \( N_D \approx 5.0 \times 10^6 \) (2.5M/fb)
  - Run1: 0.4M/fb

Factor of \( \sim 5 \) (\( \mathcal{L} \)) w.r.t run 1
Ion running

- LHC 2016 ion program now in progress
  - Big thank you for agreeing to our requests

- Requested 10 nb$^{-1}$ per direction $\sqrt{s_{NN}} = 8$ TeV
  - LHCb asymmetric

- Smooth data taking $p$Pb:
  - 5 TeV taken $\sim 2$ nb$^{-1}$
  - 8 TeV taken $\sim 13$ nb$^{-1}$
  - 95% efficiency

- Pbp taken $\sim 10$ nb$^{-1}$

- All reconstructed online

- Online plots from $p$Pb $\rightarrow$
SMOG

- Can inject He into beam pipe
  - Acts as fixed target experiment

- SMOG injected during 5 TeV pPb

- Physics goals
  - $\bar{p}$ cross sections
  - Charm production

Collisions and fixed target at the same time!!
Status of Data Processing

- 2016 proton-proton collision processing finished
- Proton-lead processing currently ongoing

Further resource usage optimization by running HLT and offline simulation workloads concurrently in the trigger farm.

E.g. during pPb Run not all resources needed for software trigger.
Limited at LHCb by crane maintenance after 24 Jan ready for detector upgrade in LS2

- Program of detector maintenance (Minor work)
  - Installation of upgrade cooling lines
  - Minor repairs to silicon tracker bonding
  - Scintillator replacements in Herschel
  - Photodetector replacements in both RICHes

- Program of infrastructure maintenance (Major work)
  - Replacement of main crane in cavern
  - Replacement of main lift to cavern
Physics overview

- 346 papers submitted (total)
  - 20 further papers within the Editorial Board
- 16 conference notes with preliminary results (2016)
- 40 other analyses under review
Publications

- **Search for decays of neutral beauty mesons into four muons** [arXiv:1611.07704]
- Evidence for the two-body charmless baryonic decay $B^+ \rightarrow p\Lambda$ [arXiv:1611.07805]
- **Measurements of charm mixing and CP violation using** $D^0 \rightarrow K^{\pm}\pi^{\mp}$ **decays** [arXiv:1611.06143]
- **Measurement of the CKM angle** $\gamma$ **from a combination of LHCb results** [arXiv:1611.03076]
- Measurement of CP asymmetry in $D^0 \rightarrow K^-K^+$ decays [arXiv:1610.09476]
- **Observation of the annihilation decay mode** $B^0 \rightarrow K^+K^-$ [arXiv:1610.08288]

cont...
Measurement of forward $\bar{t}t$, $W + \bar{b}b$ and $W + \bar{c}c$ production in $pp$ collisions at $\sqrt{s} = 8$ TeV [arXiv:1610.08142]

New algorithms for identifying the flavour of $B^0$ mesons using pions and protons [arXiv:1610.06019]

Observation of the decay $B^0_s \to \phi \pi^+ \pi^-$ and evidence for $B^0 \to \phi \pi^+ \pi^-$ [arXiv:1610.05187]

Search for the CP-violating strong decays $\eta \to \pi^+ \pi^-$ and $\eta'(958) \to \pi^+ \pi^-$ [arXiv:1610.03666]

Measurements of prompt charm production cross-sections in $pp$ collisions at $\sqrt{s} = 5$ TeV [arXiv:1610.02230]

Observation of $B^+ \to J/\psi 3\pi^+ 2\pi^-$ and $B^+ \to \psi(2S) \pi^+ \pi^+ \pi^-$ decays [arXiv:1610.01383]
Important conference on going
Measurement of $CP$ asymmetry in $B^0_s \rightarrow D^+_s K^- \pm$ decays

Measurement of time-dependent $CP$ violating asymmetries in $B^0 \rightarrow \pi^+ \pi^-$ and $B^0_s \rightarrow K^+ K^-$ decays at LHCb

**Study of the decay** $B^\pm \rightarrow D K^{\ast\pm}$ **with** $D^0 \rightarrow K^- \pi^+$, $K^- K^+$, $\pi^- \pi^+$, $\pi^- K^+$ **final states**

Search for the $B^0_s \rightarrow \eta' \phi$ decay

Search for $CP$ violation in the rare $\Lambda^0_b \rightarrow p K^- \mu^+ \mu^-$ decay

**First observation of a non-tree $B^+_c$ transition with** $B^+_c \rightarrow D^0 K^+$ **decays**

Measurement of $J/\psi$ pair production cross-section in $pp$ collisions at $\sqrt{s} = 13$ TeV

First observation of $B^0_s \rightarrow \eta_c h^+ h^-$ decays
Observation of triply charmed $B^+_c$ decays
$B^+_c \to J/\psi D(\ast) K(\ast)$

Measurement of the $B^\pm$ production asymmetry and the $CP$-violating asymmetry in the decay $B^\pm \to J/\psi K^\pm$

Observation of the $\Xi_b^- \to J/\psi \Lambda K^-$ decay

Search for long-lived scalar particle in $B^+ \to K^+ \chi(\mu\mu)$ decay

Measurement of the branching fraction ratio and $CP$ asymmetry difference of the decays $B^- \to J/\psi \pi^-$ and $B^- \to J/\psi K^-$

Observation of the rare baryonic decay $\Lambda_b^0 \to p \pi^- \mu^+ \mu^-$

Measurement of the phase difference between the short- and long-distance amplitudes in the $B^+ \to K^+ \mu^+ \mu^-$ decay
Selected physics analyses

The following analyses are grouped into:

- CP violation analysis
- Rare decays
- EW production
CKM angle $\gamma$ LHCb combination

- CKM $\gamma \equiv \arg[-V_{ud}V_{ub}^*/V_{cd}V_{cb}^*]$
  - Least well known angle of the CKM unitarity triangle
  - Measured from tree level processes

- Can combine 5 $B \rightarrow DKX$ LHCb results to improve $\gamma$ estimate
  - $DK$ combination: 71 observables and 32 parameters
  - $DK/\pi$ combination: 89 observables and 38 parameters

- Included analyses:
  - $B^+ \rightarrow DK^+$
  - $B^0_d \rightarrow DK^{*0}$
  - $B^0_d \rightarrow DK^{+}\pi^-$
  - $B^+ \rightarrow DK^{+}\pi^+\pi^-$
  - Parameterised by $\gamma$ and nuisances $r_B^{DK(*)}$ & $\delta_B^{DK(*)}$
  - Time dependent $B^0_s \rightarrow D_s^{\mp}K^\pm$
  - $B^+ \rightarrow D\pi^+$ (additional combination)
  - $B^+ \rightarrow D\pi^+\pi^-\pi^+$ (additional combination)

[arXiv:1611.03076]
Combined likelihood formed from all observables

**Just $B^+$ projections**

![Graph showing $\delta_B$ vs $\gamma$ and $r_B^D$ vs $\gamma$ for $B^+\rightarrow DK^+$, $D\rightarrow h3\pi/hh'\pi^0$ and $B^+\rightarrow DK^+$, $D\rightarrow K_S^0hh$] (LHCb)

- Light blue: $B^+\rightarrow DK^+$, $D\rightarrow h3\pi/hh'\pi^0$
- Pink: $B^+\rightarrow DK^+$, $D\rightarrow K_S^0hh$
- Orange: All $B^+$ modes
- Green: Full LHCb Combination

**Final result**

$$\gamma = (72.2^{+6.8}_{-7.3})^\circ \quad \text{(c.f prev. } 73^{+9}_{-10} \text{ LHCb 2014)}$$

$$\gamma \in [55.9, 85.2]_{95\%}$$

[arXiv:1611.03076]
$B^{\pm} \rightarrow DK^{*\pm}$ from run II data (CKM conference)

- Decay with same parameterisation
- Run 1: 3 fb$^{-1}$
  + Run 2: 1 fb$^{-1}$
- First CP in $B/D$ measurement using Run 2 data
- More inputs to $\gamma$
- Consistent with $\gamma$ combination

[LHCb-CONF-2016-014]
Mixing and CP violation in $D^0 \rightarrow K^\pm \pi^\mp$

- **Reminder:** mixing obvious in LHCb (first $5\sigma$ obs.)
- Previous analysis used $D^0$ from $pp$ collision (prompt)
- Add short decay time sample from
  \[
  \overline{B} \rightarrow D^{*+}\mu^- \\
  D^{*+} \rightarrow D^0\pi^+ \\
  D^0 \rightarrow K^\pm\pi^\mp
  \]
- **Double tagged** through charge of muon and pion
- Consistent with no CPV
  [arXiv:1611.06143]
New algorithms for identifying the flavour of $B^0$

- Time dependent CP analyses require initial flavour of $B^0$
- Same-side flavour tagging using pions and protons
- MVA trained and optimised on $B^0 \rightarrow D^- K^+$
  - Kinematics and quality of $\sim 2$ associated pions and protons and $B^0$ candidate
- 60% improvement in tagging power (eff 38% → 84%)

$\omega$ mistagging rate

[arXiv:1610.06019]
Observation of $B^0 \to K^+ K^-$

- Run 1: 3 fb$^{-1}$ data
- Control of systematics
- $>5\sigma$ significance
- First observation, rarest purely hadronic decay
- Improved measurement of $B_{s}^{0} \to \pi^{+}\pi^{-}$

\[
B(B^0 \to K^+ K^-) = (7.80 \pm 1.27 \pm 0.81 \pm 0.21) \times 10^{-8}
\]

\[
B(B_{s}^{0} \to \pi^{+}\pi^{-}) = (6.91 \pm 0.54 \pm 0.63 \pm 0.19 \pm 0.40) \times 10^{-7}
\]

[arXiv:1610.08288]
$B_c^+ \rightarrow D^0 K^+$ (CKM conference)

- Run 1: 3 fb$^{-1}$
- Expectation
  \[ \frac{f_c}{f_u} \times \mathcal{B} \sim \mathcal{O}(10^{-9}) \]
- First $b \rightarrow s$ penguin decay of $B_c$ observed
- 5.1σ significance

\[ \frac{f_c}{f_u} \times \mathcal{B}(B_c^+ \rightarrow D^0 K^+) = (9.3^{+2.8}_{-2.5} \pm 0.6) \times 10^{-7} \]

[PAPER-2016-058]
Brief aside: $P'_5$

Interest in angular observable in $B^0 \rightarrow K^{*0}\mu^+\mu^-$, $P5'$

- Discrepancy between prediction and data in dimuon invariant mass squared, $q^2$
- Could be explained by new vector, or poorly understood charm loops

- $q^2$ spectrum can distinguish between cases
- $c\bar{c}$ resonances enter the the $q^2$ spectrum
  - Unknown phases between resonances and nonresonant mode

[JHEP 02 (2016) 104]
Amplitude phase differences in $B^+ \to K^+ \mu^+ \mu^-$ decay (CKM conference)

- $q^2$ distribution of $B^+ \to K^+ \mu^+ \mu^-$ is separated from the resonant components
- Resonances: BW with phase
- Nonresonant: $C_9$, $C_{10}$
- 4 degenerate solutions $\pm \pi/2, \pm \pi/2$
- Same tools can be applied to $B^0 \to K^{*0} \mu^+ \mu^-$
- Also BF measurement

\[ \mathcal{B} (B^+ \to K^+ \mu^+ \mu^-) = (4.37 \pm 0.15 \pm 0.23) \times 10^{-7} \]

[PAPER-2016-045]
Search for the non-resonant mode in run 1 data (and MSSM scalar+pseudoscalar)

No candidates seen → limits set

\[ \mathcal{B}(B^0_{(s)} \rightarrow \mu^+ \mu^- \mu^+ \mu^-) < 2.5 \times 10^{-9} \text{ (95\% CL)} \]
\[ \mathcal{B}(B^0 \rightarrow \mu^+ \mu^- \mu^+ \mu^-) < 6.9 \times 10^{-10} \text{ (95\% CL)} \]

[arXiv:1611.07704]
**Summary**

Michael McCann on behalf of LHCb

**tt, W + bb and W + cc production**

- **Run 1**: $2 \text{ fb}^{-1} \sqrt{s} = 8 \text{ TeV}$
- $W + q\bar{q}$ test of perturbative QCD
- $W + c\bar{c}$ measurement first of its kind
- Reconstructed as two jets + isolated lepton
- Simultaneous fit to $e^{\pm}, \mu^{\pm}$, in four variables, mass of jets, and three jet flavour MVA classifiers
- $b$-tag 1/5 mistag of GPDs

\( \bar{t}t, \ W + \bar{b}b \) and \( W + \bar{c}c \) production

LHCb, \( \sqrt{s} = 8 \text{ TeV} \)

- MCFM CT10

All measurements consistent with SM
EW measurements complementary to GPDs

[arXiv:1610.08142]
Coming soon

- Time-dependent $B^0 \rightarrow \pi^+\pi^-$ and $B_s^0 \rightarrow K^+K^-$ CP violation with full Run-1 data
  - To be shown on Thursday at CKM

- Time-dependent $B_s^0 \rightarrow D_sK$ CP violation with full Run-1 data
  - To be shown on Thursday at CKM

- Lepton non-universality tests
  - $R(K)$, $R(K^*)$ & $R(D^*)$

- Plus many more
After LS2 detector read out at 40MHz, software trigger

- Velo: Si pixels
- UT: Si strips
- SciFi: scint. fibre tracker
- RICH: photon detectors & optics
- CALO: gain & readout
- Muons: shielding & readout
Upgrade progress

- Upgrade construction phase **started**
- Delivery of components **started**
  (e.g. RICH MaPMTs, SciFi fibres)
- Many important tenders completed or ongoing
  (e.g. SciFi SiPMs)
- PRR for crucial components in the coming month
  (e.g. VELO/UT sensors)
- All front-end ASICs have **passed EDR**, some PRR
- Some components on critical path:
  - Closely monitoring them and taking any urgent action
    (e.g. microchannel cooling)
- Internal comprehensive review of whole upgrade project
  - Planned for 30 January – 1 February 2017
  - Focus on critical aspects, organization of construction and preparation for installation

**Now for some evidence...**
Upgrade progress

CALO FE ASIC

SiPM for SciFi

RICH QA setup

RICH PD array
Test beam period early November

- Testing:
  - Sensors
  - Electronics
  - DAQ chain

- Involving:
  - Velo
  - UT
  - SciFi
  - RICH
  - Calorimeter

Cherenkov ring using new RICH photon detectors and electronics
Thank you to LHC for making this a great year

- Operations
  - Automation makes running the detector very easy
  - Excellent performance during $pp$ program
  - $pPb$ program ahead of expectation

- EYETS
  - Planning complete
  - Several upgrade activities already planned

- Physics
  - On course to improve on last year’s paper count
  - Still interesting results coming out of run 1
  - First results from run 2

- Upgrade
  - Many items in production
  - On course for LS2
Dead time

- **Cause (in general)**
  - Veto of consecutive triggers
  - Readout time of high occupancy events
  - Processing time of large events

- LHCb readout limited to 1 MHz events

- Can trigger nicer events with more bunches
  - Dead time will reduce with more bunches
  - Hopefully achieved next year
VELO microchannel cooling

- Initial slip in schedule
  - No further slips

- Prototype preproduction run for early next year
  - Performance check
  - Production yield check
  - Determine total cost

- Plan B in place
  - Using capillaries

- On schedule, but limited scope for delays
LHCb Integrated Luminosity in p-p in 2016

- Delivered Lumi: 1906.01 /pb
- Recorded Lumi: 1665.12 /pb
LHCb Average Mu in p-p in 2016

Average Mu

LHC Fill Number

LHCb Average Mu in p-p in 2016

LHC Fill Number

Average Mu

LHC Fill Number