LHCb highlights

- Flavour physics
  - a topic of intrinsic interest
  - a tool for indirect discovery

- LHCb overview

- Selected recent results
  - Rare decays & FCNCs
  - CPV & unitarity triangle tests
  - Spectroscopy & exotics

- Run 2 and the voyage beyond

Guy Wilkinson, University of Oxford and CERN, June 2015
What is flavour physics?

The concept of ‘flavour’ in particle physics relates to the existence of different families of quarks*, and how they couple to each other

_i.e._ 6 known flavours of quark, grouped into 3 generations

Open questions:

- why 3 generations ?
- why do the quarks exhibit this striking hierarchy in mass ?

No answer yet !
These values (i.e. ‘3’ & the masses) are free parameters of the SM

These mysteries make the ‘flavour sector’ of the Standard Model of great interest.

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Highlights of LHCb Erice, Guy Wilkinson

* the concept of flavour extends to the lepton sector too

June 2015
Flavour and the CKM matrix

In the Standard Model quarks can only change flavour through emission of a $W$ boson \textit{(i.e.} weak force\textit{)}. For example a $t$ quark can decay into a $b$, $s$ or $d$ quark:

But these decays are not equally likely. At the amplitude level they are weighted by factors that are elements of the Cabibbo-Kobayashi-Maskawa (CKM) matrix, and these factors vary dramatically – here is another hierarchy we don’t understand!

These elements of the CKM matrix are also fundamental parameters of the Standard Model. Why they have these values is another great mystery.

The CKM matrix is also linked to another big puzzle of flavour physics…
CP violation

CP violation (CPV) → difference in behaviour between matter and anti-matter.

First discovered in the kaon system in 1964, opportunities of study were limited until colliders arrived that could make lots & lots of $b$-quark hadrons, e.g. the LHC

A recent example from LHCb - look at $B$ meson decaying into a pion & two kaons…

...the decay probabilities are manifestly different for $B^-$ & $B^+$! In the Standard Model CPV is accommodated, *but not explained*, by an imaginary phase in the CKM matrix
Breaching the walls of the Standard Model

The LHC is searching for New Physics - to find this we need to get behind the walls of the Standard Model fortress. There are two strategies used in this search.

**Direct**

Use the high energy of the LHC to produce the New Physics particles, which we then detect.

**Indirect**

Make precise measurements of processes in which New Physics particles enter through ‘virtual loops’.

Both methods are powerful. LHCb specialises (mostly) in the ‘indirect’ approach.
Indirect measurements – an established tradition in science

Eratosthenes was able to determine the circumference of the earth using indirect means…

...around 2.2 thousand years prior to the direct observation.
Indirect measurements – an established tradition in science

In flavour physics the guiding principle is to probe processes where loop diagrams are important, as here non-SM particles may contribute

(but as we will see, tree-mediated decays also have their role to play)

Indirect search principle: Precise measurements of low energy phenomena tells us about unknown physics at higher energies
Indirect measurements – an established tradition in science

In flavour physics the guiding principle is to probe processes where loop diagrams are important, as here non-SM particles may contribute

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Indirect search principle \[\rightarrow\] Precise measurements of low energy phenomena tells us about unknown physics at higher energies
LHCb – a flavour physics experiment at the LHC

A collaboration of ~1100 members from 68 institutes in 16 countries

An experiment to search for physics beyond the Standard Model, through flavour studies of beauty- and charm-hadrons (and general forward physics)
LHCb – a forward spectrometer for flavour physics

The VELO is a silicon detector around the interaction point. It approaches within 8 mm of the beamline and reconstructs the $b$-hadron decay vertex precisely.

One-half of the VELO under construction

A reconstructed $b$-hadron decay vertex

June 2015
LHCb – a forward spectrometer for flavour physics

Two ‘RICH’ detectors detect Cherenkov radiation. the angle at which this is emitted tells us the particle species – it provides ‘hadron identification’.
LHCb – a forward spectrometer for flavour physics

A 4Tm dipole, and the tracking detectors reconstruct the trajectory of charged particles, and allows their momentum to be determined.
LHCb – a forward spectrometer for flavour physics

The calorimeter system (ECAL & HCAL) reconstructs the energy of photons, electrons and hadrons. The muon system (M1-M5) identifies muons.

Part of calorimeter system (preshower)

These detectors are particularly important for the role they play in the LHCb trigger.
LHC run 1 went from 2010 to 2012, during which LHCb collected 3 fb$^{-1}$ of data (this corresponds to $\sim 3 \times 10^{11}$ $b$ anti-$b$ pairs being produced within LHCb).

We have just emerged from a 2 year shutdown, necessary to upgrade LHC energy. Run 2 will go to end of 2018 – we aim to increase our beauty sample by x3 or more.
LHC run 1 went from 2010 to 2012, during which LHCb collected 3 fb$^{-1}$ of data (this corresponds to $\sim 3 \times 10^{11} b$ anti-$b$ pairs being produced within LHCb).

LHCb deliberately operates at lower luminosity than ATLAS/CMS.

This is (current) best choice for precision $b$-physics measurements.

We have just emerged from a 2 year shutdown, necessary to upgrade LHC energy. Run 2 will go to end of 2018 – we aim to increase our beauty sample by x3 or more.
Selected physics results

Highlights of LHCb
Erice, Guy Wilkinson

June 2015
Over 260 physics publications (run-data still being harvested). Here will focus on selected results from three areas:

- Rare decays & FCNCs
- CPV & unitarity triangle tests
- Spectroscopy & exotics

But LHCb’s forward acceptance and special instrumentation gives it unique capabilities in many other areas of physics.
**Experimental glossary**

To understand LHCb’s role it is useful to know the context of previous & current experiments

### b-factories

**BaBar (SLAC) & Belle (KEK)**

Operated in the 2000’s e⁺e⁻ machines with asymmetric beams for time-dep studies, mainly at Υ(4S), hence $B^0$ and $B^+$ samples. Considered ‘clean’ environments.

**Tevatron experiments**

**CDF & D0**

Tevatrons ‘general purpose detectors’. Pioneered $b$-physics in hadronic collisions. Important early $B_s$ and $b$-baryon studies.

**ATLAS & CMS**

Their excellent instrumentation gives them great capabilities in certain $b$-physics channels, especially those with dilepton final states.
‘Rare decays’ and FCNCs

- In search of the super-rare: $B_{s,d} \rightarrow \mu^+\mu^-$
- Electroweak penguins: $B \rightarrow K^{(*)} l^+l^-$
- Trouble at tree-level: $B \rightarrow D^{*}\tau\nu$
FCNCs: the search for $B_s \rightarrow \mu\mu$

This decay mode can only proceed through suppressed loop diagrams.

In the Standard Model it happens extremely rarely ($\sim 10^{-9}$), but the exact rate is very well predicted.

Many models of New Physics (e.g. SUSY) can enhance rate significantly!

A ‘needle-in-the haystack’ search, which has been pursued for over 25 years.

Since 2010 LHCb has been using, and refining, a multivariate (BDT) approach.
$B_s \rightarrow \mu \mu$ - progress through run 1

Plot of invariant mass distribution in region of high BDT sensitivity – if there is a signal we should see a peak here (but the BDT uses much more information than the invariant mass alone!)

[PLB 708 (2012) 55]

2010
Nothing
**$B_s \rightarrow \mu\mu$ - progress through run 1**

Plot of invariant mass distribution in region of high BDT sensitivity – if there is a signal we should see a peak here (but the BDT uses much more information than the invariant mass alone!)

*Maybe a hint of a bump, but nothing can be claimed*
$B_s \rightarrow \mu\mu$ - progress through run 1

Plot of invariant mass distribution in region of high BDT sensitivity – if there is a signal we should see a peak here (but the BDT uses much more information than the invariant mass alone!)

First evidence that there is something there!

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$B_s \rightarrow \mu\mu$ progress through run 1

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Highlights of LHCb
Erice, Guy Wilkinson
June 2015
$B_s \to \mu\mu$ - progress through run 1

Plot of invariant mass distribution in region of high BDT sensitivity – if there is a signal we should see a peak here (but the BDT uses much more information than the invariant mass alone!)

The evidence grows…
LHCb and CMS physicists have now performed a combined fit to their datasets, making use of common assumptions. The first combination of results from the LHC !

Included also are results for the even rarer $B_{d,s} \rightarrow \mu\mu$, where a signal may be emerging too. The picture is intriguing and provides encouragement for run 2 !

\[ B(B_s^0 \rightarrow \mu^+ \mu^-) = \left( 2.8^{+0.7}_{-0.6} \right) \times 10^{-9} \quad (6.2\sigma) \]

\[ B(B^0 \rightarrow \mu^+ \mu^-) = \left( 3.9^{+1.6}_{-1.4} \right) \times 10^{-10} \quad (3.0\sigma) \]

LHCb and CMS physicists have now performed a combined fit to their datasets, making use of common assumptions. The first combination of results from the LHC!

\[ B_{d,s} \rightarrow \mu\mu: \text{run-1 legacy paper and CMS-LHCb combination} \]

Included also are results for the even rarer \( B_d \rightarrow \mu\mu \), where a signal may be emerging too. The picture is intriguing and provides encouragement for run 2!
Decays such as $B^0 \rightarrow K^* \mu^+ \mu^-$ offer many observables which probe helicity structure of any New Physics...

The $B$-factory experiments had inadequate statistics for meaningful tests. This has now all changed, e.g. forward-backward asymmetry vs dilepton $q^2$.

Loop diagrams mediating decay

Belle: ~250 $K^* \mu^+ \mu^-$ candidates

Hint of lying above prediction
Decays such as $B^0 \rightarrow K^* \mu^+ \mu^-$ offer many observables which probe helicity structure of any New Physics...

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Decays such as $B^0 \rightarrow K^*\mu^+\mu^-$ offer many observables which probe helicity structure of any New Physics...

The $B$-factory experiments had inadequate statistics for meaningful tests. This has now all changed, e.g. forward-backward asymmetry vs dilepton $q^2$.

But there are many other observables, which can be built from the measured amplitudes, & are constructed to be intrinsically robust against form factor uncertainties, e.g. “$P_5$”.
One such observable is $P_5'$: this showed a local discrepancy in the 1 fb$^{-1}$ analysis which has persisted in the 3 fb$^{-1}$ update.

There are other several slightly odd results in $b \rightarrow s l^+l^-$ decays...

...which some (non-LHCb) people have sought to explain in a coherent way, e.g. through Wilson coefficient analysis.

Does this point to New Physics or underestimated theory errors? Time and run 2 will tell us more!
Hints of lepton-flavour violation in $B \rightarrow K l^+ l^-$?

FCNC processes are also an excellent place to look for evidence of New Physics effects in contraction to the SM paradigm of lepton universality.

Example - test of lepton universality through $R_K$, the ratio of $B \rightarrow K \mu^+ \mu^-$ to $B \rightarrow Ke^+ e^-$ [PRL 113 (2014) 151601]

Control region gives $R_K$ consistent with unity. Interesting, low $q^2$ region gives:

$$R_K = 0.745^{+0.090}_{-0.074} \text{ (stat)} \pm 0.036 \text{ (syst)}$$

which is 2.6σ from unity (3σ if BaBar included).

Follow up studies underway, e.g. $B \rightarrow K^* l^+ l^-$

This is not the first hint of LFV effects in B decays…
\[ R(D^*) \equiv \frac{\text{BR}(B \to D^{*}\tau\nu)}{\text{BR}(B \to D^{*}\mu\nu)} \]

\( B \to D^{*}\tau\nu \) is not a FCNC, nor even particularly rare, but of great interest, because of its sensitivity to the charged Higgs sector & the \( B \)-factory legacy.

A very suggestive pattern of measurements!

Interesting tension in \( R(D) \) too, but taken together they are not compatible with e.g. type-II 2HDM.

Something that LHCb cannot do due to impossibility of reconstructing full event?
$R(D^*) \equiv \frac{\text{BR}(B \rightarrow D^*\tau\nu)}{\text{BR}(B \rightarrow D^*\mu\nu)}$ at LHCb

One $q^2$ bin:

Reconstruct $B^0 \rightarrow D^*\tau\nu$ with $\tau \rightarrow \mu\nu\nu$,

Demand good vertex separation and isolation with dedicated MVA

Approximate $B$ momentum from boost of reconstructed signal.

Disentangle from $B^0 \rightarrow D^*\mu\nu$ and other backgrounds by fitting against $E_{\mu}^*$ and $m_{\text{miss}}^2$ in bins of $q^2$

$$R(D^*) = 0.336 \pm 0.027 \pm 0.030$$

Similar to BaBar central value and 2.1 $\sigma$ above the SM!
\[ R(D^*) \equiv \frac{\text{BR}(B \rightarrow D^*\tau\nu)}{\text{BR}(B \rightarrow D^*\mu\nu)} \] at LHCb

Current global picture:

Wait for global average of these and \( R(D) \) results.
Hope for more out of run-1 data with other decay modes, and run-2 data. At the LHC the impossible is possible!
CPV and unitarity triangle tests

- Matter-antimatter trigonometry
  - the angle $\gamma$
  - $\sin 2\beta$
  - $V_{ub}$

- Search for CPV in the $B_s$ sector
Matter-antimatter trigonometry

The Unitarity Triangle is a geometrical description of $CP$-violation within the context of the Standard Model, which in the flavour sector is the CKM mechanism. We must check its consistency through precise measurements.

The $B$ factories did a fantastic job and showed that the CKM paradigm dominates the picture, but New Physics contributions can still be lurking at $\sim 20\%$ level.

Let’s see how LHCb is advancing this programme…

\[ \frac{V_{ub}}{V_{cb}} \]

…through three key measurements.
Matter-antimatter trigonometry: $\gamma$

A precise measurement of the angle $\gamma$ is a raison d’être of LHCb.

Look in $B^{\pm} \to DK^{\pm}$ decays using common mode for $D^0$ & $D^0$

$\to \gamma$ sensitive interference

$\to$ different rates for $B^+$ & $B^-$ (CPV!)

Many possibilities: $K\pi$, $KK$, $K\pi\pi\pi\pi$...

Tree-level decays: strategy very clean & yields result unpolluted by New Physics

This is a good thing! Provides SM benchmark against which other loop-driven NP sensitive observables can be compared (e.g. $\Delta m_d/\Delta m_s$, $\sin2\beta$, $\gamma$ measured in $B\to hh$)
The story so far...

Derived from combination of observables in many $B\rightarrow DK$ decay channels

Consistent with the indirect prediction...

...but not nearly as precise

Indirect prediction from rest of triangle

...factor 3 improvement in 10 years.
γ measurement: true precision needs statistical muscle of LHCb

Rare, important decays just beyond the reach of the B-factories (e.g. the suppressed ‘ADS’ $B^\pm \rightarrow (K^\pm \pi^\pm)_D K^\pm$ mode (BR ~ $10^{-7}$) was soon seen at LHCb

This CP asymmetry carries ultra-clean, easy to interpret, information on $\gamma$!
Measurement of $\gamma$: $B \rightarrow DK$ at LHCb

Sometimes CPV involves looking for $B^-$ / $B^+$ differences in multibody phase space, e.g. $D \rightarrow K_S \pi \pi$ or $K_S K K$. In all cases benefit from the surprising (?) purity of signal.

This cleanliness thanks to:

- excellent particle ID and vertexing
- separation of $D$ and $B$ vertices

Seen in all modes that enter the $\gamma$ analysis, even those with $\pi^0$'s (once thought ‘impossible’ at the LHC).
LHCb: current precision on $\gamma$ and future prospects

Combination of LHCb $B \rightarrow DK$ results obtained so far

Uncertainty of $<10^\circ$ - better than that obtained with combined B-factory samples

Will improve steadily:

• still many important run 1 modes to be published (e.g. 3 fb$^{-1}$ $B \rightarrow D(KK, \pi\pi, K\pi, K\pi\pi, \pi\pi\pi, \pi\pi\pi\pi)K$, $B_s \rightarrow D_s K$)

• Repeat with much larger data set anticipated in run 2.

Aim for $\sim 3^\circ$ uncertainty after run 2 (matches current indirect precision)
Measurement on $\beta$ was the legacy of the $B$-factories, and helped pave way for 2008 Nobel Prize for Kobyashi and Maskawa. Now LHCb has entered the game!

This measurement requires time-dependent measurement & flavour tagging, which is trickier at a hadron collider than at an $e^+e^-$ machine.

Precision obtained by LHCb with $B^0 \rightarrow J/\Psi K_S$ is very similar to that of the $B$-factories. LHCb will dominate measurement with run-2 data. Upgrade prospects exciting!
Matter-antimatter trigonometry: $V_{ub}$

Measurement of $V_{ub}$ long thought essentially impossible at LHC. Challenging to separate $b \rightarrow u \mu \nu$ and $b \rightarrow c \mu \nu$ processes without any beam energy constraint.

We have now shown it can be done! Use baryon decay $\Lambda_b \rightarrow p \mu \nu$ and benefit from RICH & vertexing capabilities.

Very precise result:

$$|V_{ub}| = (3.27 \pm 0.15 \pm 0.16 \pm 0.06) \times 10^{-3}$$

Brings new insight to long-standing ‘inclusive vs exclusive’ $V_{ub}$ puzzle.

Normalise to $\Lambda_b \rightarrow \Lambda_c \mu \nu$ and use lattice QCD to interpret result.
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Still much to understand, but new LHCb result, as with $B \to D^* \tau\nu$, has redefined the ‘art of the possible’ for $B$-physics at hadron machines!

Look out for complementary measurements, *e.g.* with $B_s \to K \mu\nu$.

Normalise to $\Lambda_b \to \Lambda_c \mu\nu$ and use lattice QCD to interpret result.
Mixing induced CPV in $B_s$ system

CPV phase, $\varphi_s$, in $B_s$ mixing-decay interference, e.g. measured in $B_s \to J/\Psi \Phi$, very small & precisely predicted in SM. Box diagram offers tempting entry point for NP!

Tevatron results were tantalising with early data and remain intriguing with final sample:

Results are consistent, & both are $\sim 1\sigma$ away from SM. What about the LHC?
Mixing induced CPV in $B_s$ system

CPV phase $\phi_s$ in $B_s$ mixing-decay interference, e.g. measured in $B \rightarrow J/\Psi \Phi$, very small & precisely predicted in SM.  Box diagram offers tempting entry point for NP!

Results are consistent, & both are $\sim 1\sigma$ away from SM.  What about the LHC?

LHCb designed with excellent time resolution, necessary to resolve the rapid $B_s$-$\bar{B}_s$ oscillations:

In addition: additional channels and very large data samples.

Tevatron results were tantalising with early data and remain intriguing with final sample:

[PRD 85 (2012) 072002]
[PRD 85 (2012) 032006]

LHCb has now completed its run-1 measurement of $\phi_s$, attaining a precision $\sim 20\times$ better than Tevatron in $B_s \rightarrow J/\psi \phi (KK)$ [PRL 114 (2015) 041801] & adding important new modes e.g. $B_s \rightarrow J/\psi \pi \pi$ [PLB 736 (2014) 186]. Earlier hints of large NP effects have gone…

...but observable remains a priori very sensitive to non-SM contributions and essential to improve precision in run 2, and in particular at Upgrade.
Spectroscopy & the search for exotics

• New baryons
• Unambiguous observation of a four-quark hadron

The fabled basilisk
Many new states found by LHCb, most of which fit within the ‘vanilla’ quark model
e.g. baryons: the discovery of the
$\Xi_{b}^{-'\ -}$ and $\Xi_{b}^{*-'\ -}$ [PRL 114 (2015) 062004]

\[ m(\Xi_{b}^{-'\ -}) - m(\Xi_{b}^{0}) - m(\pi^{-}) = 3.653 \pm 0.018 \pm 0.006 \text{ MeV}/c^{2}, \]
\[ m(\Xi_{b}^{*-'\ -}) - m(\Xi_{b}^{0}) - m(\pi^{-}) = 23.96 \pm 0.12 \pm 0.06 \text{ MeV}/c^{2}, \]
\[ \Gamma(\Xi_{b}^{-'\ -}) = 1.65 \pm 0.31 \pm 0.10 \text{ MeV}, \]
\[ \Gamma(\Xi_{b}^{*-'\ -}) < 0.08 \text{ MeV at 95\% C.L.} \]
Spectroscopy

Many new states found by LHCb, most of which fit within the ‘vanilla’ quark model 

*e.g.* baryons: the discovery of the $\Xi_b^-$ and $\Xi_b^{*-}$ [PRL 114 (2015) 062004]


"Baryons can now be constructed from quarks by using the combinations $qqq$, $qqqqq$, etc., while mesons are made out of $q\bar{q}$, $qqqq\bar{q}$, etc.

Murray Gell-Mann"
Spectroscopy - exotics

\( Z(4430) \) seen by Belle in \( B \to \Psi'K\pi \) but not confirmed by BaBar.

LHCb has a very large and clean sample...

...which leaves little doubt that something is there.

But can this structure be produced by a combination of known resonances?

No! \( \rho \)-value of complete fit goes from \( 10^{-6} \) with only standard mesons included to 12\% with ‘exotic’ component present.

Furthermore, ‘bump’ shows textbook resonance behaviour.

Unambiguous observation of a \textit{four-quark} state (\textit{not} ‘vanilla’!)
Spectroscopy - exotics

Again, plenty of interest in the press (and beyond):

Unambiguous observation of a four-quark state (not ‘vanilla’!)
Spectroscopy - exotics

Again, plenty of interest in the press (and beyond):

Montreux jazz festival, 2014

Unambiguous observation of a four-quark state (not ‘vanilla’!)

Z(4430) for saxophone quartet by Roger Zare

Z(4430) - seen by Belle in B→Ψ’KK but not confirmed by BaBar.

LHCb has a very large and clean sample...

But can this structure be produced by a combination of known resonances?...

...which leaves little doubt that something is there.

%bckgd ~4% ’Vanilla’ (no Z)

Z[ PRL 112 (2014) 222002]
Run 2 and the voyage beyond

The straits of Messina: sailing between Charybdis and Scylla
LS1 activities – preparing for run 2

A very busy time – all work completed successfully and on schedule. Many improvements & small repairs.

- Removing RICH photodetectors for maintenance
- Closing muon filter
- Re-mapping dipole field
- Reinserting beampipe
- Infrastructure - building a new control room
- Closing TT
Run-2 restart

We successfully closed the VELO & participated in first stable beam fill at 13 TeV.

We have run without problem in fills since then, data taking for detector calibration, trigger tuning, calibrating & aligning, & preparing for physics production.

We are all ready to go! Note that our run 2 operation is far from identical to run 1…
Run-2 operation

Several ambitious changes planned for operation during run 2 aimed at increasing physics output and making optimal use of resources.

HLT split into two steps, with HLT2 not run until calibration and alignment validated.

This means the trigger runs with offline-like performance → better background rejection.

Furthermore, we can dare to use some of the trigger output directly for physics analysis without any offline processing! This we call the ‘TURBO stream’.

Including several kHz of ‘TURBO’
Run 2 – first data from ‘Turbo’ stream

Charm signals from Turbo stream as reconstructed in one of first fills of run 2.

Recall: full reconstruction run in trigger – physics quality with no further offline processing needed!
LHCb Upgrade in a nutshell

An LHCb Upgrade is scheduled, with installation in LS2 and first data-taking in run 3. The motivation is to take increased advantage of the huge rate of heavy-flavour production at the LHC.

The LHCb Upgrade

1) **Full software trigger**
   - Allows effective operation at higher luminosity
   - Improved efficiency in hadronic modes

2) Raise operational luminosity by factor five to $2 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$

Necessitates redesign of several sub-detectors & overhaul of readout

Huge increase in precision, in many cases to the theoretical limit, and the ability to perform studies beyond the reach of the current detector.

Flexible trigger and unique acceptance also opens up opportunities in other topics apart from flavour (‘a general purpose detector in the forward region’).
Upgrade overview

Current detector
Upgrade overview

Current detector → upgraded detector

All sub-detectors read out at 40 MHz for software trigger
Upgrade overview

Current detector → upgraded detector

Replacement of full tracking system

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

Pixel Vertex Locator (VELO)

Half of VELO system

Improved performance

(`UT` = ‘Upstream tracker’, a high performance Si strip detector)
Upgrade overview

Current detector → upgraded detector

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

Scintillating Fibre Tracker

Replacement of full tracking system

Large scale system (~12,000 km of fibres)
Upgrade overview

Current detector → upgraded detector

RICH 1 redesigned; new photodetectors installed for RICH 1 and RICH 2

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

Replacement of full tracking system

RICH system

New photodetector

New optics…

...good performance at high luminosity
Upgrade overview

Current detector → upgraded detector

RICH 1 redesigned; new photodetectors installed for RICH 1 and RICH 2

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

Replacement of full tracking system

Calorimetry and muons:
- Redundant components of system removed; new electronics added; more shielding included
Completion of upgrade TDRs

All* upgrade TDRs have now been approved by the Research Board. We have final & achievable technology choices for all systems.

We have now organised ourselves for the next phase of the programme, i.e. final stages of R&D, engineering and production readiness reviews, and production.

* Caveat: a computing TDR is foreseen for Q1 2017.
Conclusions

LHCb continues to produce world-leading results in flavour-physics (and beyond)
- some of these are in topics previously thought inaccessible to the LHC
- some of these are intriguing…

Much to look forward to in the coming years
- LHCb in excellent shape for run-2 data-taking
- Exciting Upgrade on schedule for run 3
Backups
LHCb – the essentials

LHCb – a forward spectrometer optimised for heavy-flavour physics at the LHC

• forward acceptance (2 < |η| < 5)
• high bandwidth trigger
• acceptance down to low $p_T$
• precise vertexing (VELO)
• hadron identification (RICHes)

LHCb operation proceeds in harmony with higher luminosity operation of ATLAS/CMS thanks to luminosity leveling.

• 37 pb$^{-1}$ collected in 2010
• 1 fb$^{-1}$ in 2011 and 2 fb$^{-1}$ in 2012
• aim for ~6-7 fb$^{-1}$ during run 2

>260 papers & counting on CP violation, rare decays & spectroscopy (+ EW, QCD, ion physics… no time to cover here)
The angle $\theta_K$ is defined as the angle between the
direction of the $K^+$ ($K^-$) and the $B^0$ ($\bar{B}^0$) in the rest frame of the $K^{*0}$ ($\bar{K}^{*0}$) system. The
angle $\phi$ describes the angle between the plane defined by the $\mu^+$ and $\mu^-$ and the plane
defined by the kaon and pion in the $B^0$ ($\bar{B}^0$) rest frame.

$$
\frac{1}{d(\Gamma + \bar{\Gamma})/dq^2} \frac{d^3(\Gamma + \bar{\Gamma})}{d\Omega} \bigg|_p = \frac{9}{32\pi} \left[ \frac{3}{4} (1 - F_L) \sin^2 \theta_K + F_L \cos^2 \theta_K \right. \\
\left. + \frac{1}{4} (1 - F_L) \sin^2 \theta_K \cos 2\theta_l \\
- F_L \cos^2 \theta_K \cos 2\theta_l + S_3 \sin^2 \theta_K \sin^2 \theta_l \cos 2\phi \right. \\
+ S_4 \sin 2\theta_K \sin 2\theta_l \cos \phi + S_5 \sin 2\theta_K \sin \theta_l \cos \phi \\
+ \frac{4}{3} A_{FB} \sin^2 \theta_K \cos \theta_l + S_7 \sin 2\theta_K \sin \theta_l \sin \phi \\
+ S_8 \sin 2\theta_K \sin 2\theta_l \sin \phi + S_9 \sin^2 \theta_K \sin^2 \theta_l \sin 2\phi \right]
$$

$$
P'_{4,5} = \frac{S_{4,5}}{\sqrt{F_L(1 - F_L)}}
$$
$B \rightarrow [K_{shh}]_D K$ at LHCb

$B \rightarrow DK$ method has been applied by LHCb to $D \rightarrow K_S \pi \pi \pi$ and $K_S KK$. CPV leads to difference in $D$ Dalitz plots for $B^+$ and $B^-$ decays.

Data analysed in bins which have similar $D$ decay strong-phase. To retain model independence these phases are taken from measurements of quantum-correlated $DD$bar pairs at CLEO-c [PRD 82 (2010) 112006] - will be improved by BES-III.

Cleanliness of measurement preserved exploiting synergy of facilities!
The elephant in the room: $a_{sl}$

Flavour-specific CP asymmetry in $B$ decays, most easily measured in semileptonic (hence $a_{sl}$) accesses CP-violation in mixing. Extremely small in SM, especially in $B_s$ system.

[D0, PRD 89 (2014) 012002]

D0 measurement, made with dileptons, measures a superposition of $a_{sl}^s$ and $a_{sl}^d$.

Result lies $\sim 3\sigma$ from SM (exact degree of tension depends on how comparison is made).

Most usually interpreted as a $B_s$ driven effect. Challenging, however, to reconcile with other measurements, e.g. $B_s \rightarrow J/\Psi \phi, J/\Psi \pi \pi \pi$. 
Attempting to resolve the D0 dimuon anomaly

Systematics associated with being a pp collider makes it very difficult to repeat D0 measurement at LHC. However it is possible to measure $a_{sl}^s$ and $a_{sl}^d$.

LHCb has performed 1 fb$^{-1}$ $a_{sl}^s$ [PLB (728) (2014) 607] and 3 fb$^{-1}$ $a_{sl}^s$ [arXiv:1409.8586] studies.

These recent measurements agree with SM, but do not exclude dimuon result. New, much more precise $a_{sl}^s$ result on way. Improved $\Delta \Gamma_d/\Gamma_d$ would also be welcome.
Charmless $B$ decays

Other surprises are emerging from the large samples now available at the LHC - not all necessarily with New Physics consequences, but still of great interest. *e.g.* large CPV seen in low mass non-resonance region of 3-body decays

Perhaps due to long-distance $\pi\pi \leftrightarrow KK$ rescattering?
The charm renaissance

For many years charm was the ‘Cinderella’ of flavour physics studies

- tiny CPV and mixing effects expected in the SM…
- …and no evidence of either despite intensive searches
- long-distance effects complicate predictions

→ mixing parameters not tiny (~1%); good news for (indirect) CPV observables
→ smallness of SM ‘pollution’ not a bad thing in looking for New Physics signal
→ internal down-type quarks in loops – complementary to $b$-physics
→ huge potential of LHC for improving sensitivity

"All results are null.”
Ian Shipsey, Charm 2006.

Then combination of B-factory analyses finally saw mixing. New outlook!

Measurement contours; no-mixing excluded at 5σ

No-mixing excluded at lots and lots

Excluded regions

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Rise of the hadron machines

Power of hadron colliders is now clear. Last year LHCb and CDF published first individual (>5σ measurements, in WS $K\pi$ analyses.

Although $e^+e^-$ machines retain advantages for many modes with neutrals, LHC has huge advantages for charged modes (e.g. # WS $K\pi$ in Run 1 at LHCb = 230 x 10^3 ; at Belle in 0.9 ab⁻¹ = 12 x 10^3) and also time resolution.
\[ \Delta A_{\text{CP}}: \text{first sighting of direct CPV in charm?} \]

The observable \( \Delta A_{\text{CP}} \equiv A_{\text{CP}}(K\bar{K}) - A_{\text{CP}}(\pi\pi) \) is robust against detector systematics & production asymmetries, and is sensitive to any direct CPV in SCS charm decays.

Majority opinion in literature before 2012:

\[ \rightarrow \text{direct CPV at or above a few per-mille in SCS decays is very unlikely in SM} \]

Hence LHCb result [PRL 108 (2012) 111602] with 0.6 fb\(^{-1}\) of \( D^* \) decays of great interest:

\[ \Delta A_{\text{CP}} = \left[ -0.82 \pm 0.21 \text{(stat.)} \pm 0.11 \text{(syst.)} \right] \% \]

Soon after, measurements from CDF 9.7 fb\(^{-1}\) [PRL 109 (2012) 111801] and Belle 976 fb\(^{-1}\) [arXiv:1212.1975] increased the excitement:

\[ \Delta A_{\text{CP}} = (-0.62 \pm 0.21 \text{ (stat)} \pm 0.10 \text{ (syst)})\% \]

CDF

\[ \Delta A_{\text{CP}}^{hh} = (-0.87 \pm 0.41 \pm 0.06)\% \]

Belle

These (together with other measurements) only consistent with no-CPV at \(~2\%\).

A story to get the theorists interested? Yes! And surely very unlikely to be SM ????
$\Delta A_{CP}$: too early to celebrate

So it seemed a consistent picture had emerged of $\sim0.5\%$ direct CPV in SCS charm decays (thanks to LHCb, CDF, Belle) This caused the theory community to re-evaluate their position...

…but later LHCb results ($1\text{ fb}^{-1}$ $D^*$ update [LHCb-CONF-2013-003] and $3\text{ fb}^{-1} B\rightarrow D^0\mu X$ [JHEP 07 (2014) 041]) indicate reduced / $\sim$null effect

Next steps required for progress:

• Final LHCb $D^*$ results from 2012 data set (& beyond)
• More precise results in other SCS modes
Recent progress in SCS direct CPV searches

Other two-body (\& pseudo-body) SCS searches now have 0.1\% precision, \textit{e.g.} $D^+ \to \Phi \pi^+$

\begin{align*}
(-0.04 \pm 0.14 \pm 0.14)\% & \quad \text{LHCb [JHEP 06 (2013) 112]} \\
(+0.51 \pm 0.28 \pm 0.05)\% & \quad \text{Belle [PRL 108 (2012) 071801]} \\
(-0.3 \pm 0.3 \pm 0.5)\% & \quad \text{BaBar [PRD 87 (2012) 052010]}
\end{align*}

Moreover a developing area, of great promise, is to look for regions of local CPV in multi-body modes, where interference between neighbouring resonances may allow effects to be seen.

\textit{e.g.} LHCb analysis of 0.7 M $D^0 \to \pi^+ \pi^- \pi^0$ decays with model independent ‘energy’ test [PLB 740 (2015) 158]

Prospects of direct CPV revealing clear sign of NP appears to be receding. But still of \textit{great} interest to find a non-0 signal – and LHCb statistics hold promise.
CPV searches in mixing

More important is to search for CPV in mixing related phenomena. Observables are pre-multiplied by x,y, so ‘large’ (~1%) value of mixing is encouraging in this quest.

Already plenty of progress in last few years…

…any non-zero signal with current and near-future precision would indicate NP.
Searching for indirect CPV

Hunt for indirect CPV can be performed with:

- Dedicated observables, such as $A_T$

$$A_T \equiv \frac{\Gamma(D^0 \to KK) - \Gamma(D^0 \to KK)}{\Gamma(D^0 \to KK) + \Gamma(D^0 \to KK)}$$

(similarly for any other CP eigenstate)

$$A_T = \frac{1}{2} \left[ \left( \frac{q}{p} \right) y \cos \phi - \left( \left| \frac{p}{q} \right| + \left| \frac{p}{q} \right| \right) x \sin \phi \right]$$

(neglecting direct CPV)

Current precision 0.05% and is LHCb driven. Significant improvements already expected with full run 1 data set.

- Generalising WS $K\pi$ fit to $D^0$ and $D^0$bar
  
  e.g. LHCb PRL 111 (2013) 251801

- Time-dependent Dalitz studies of multi-body decays, e.g. $K_S\pi\pi$
  
  First LHCb run-1 results coming very soon

We’re at the start of a long journey – let’s travel hopefully!
**FCNCs: beyond the $b$**

LHCb performs strongly in the study of FCNC searches in rare charm decays, attaining world leading sensitivities, e.g. 1 fb$^{-1}$ $D^0 \rightarrow \mu\mu$ result

$$B(D^0 \rightarrow \mu^+\mu^-) < 6.2 (7.6) \times 10^{-9} \text{ at } 90\% (95\%) \text{ CL}$$

This will improve with full run-1 data set and beyond – interesting region is $\sim 10^{-10}$.

Also of growing interest is the experiment’s potential in kaon and hyperon decays. $s \rightarrow d$ transitions of interest because SM ‘background’ is highly suppressed.

$$A = A_0 \left[ c_{SM} \frac{1}{M_W^2} + c_{NP} \frac{1}{\Lambda^2} \right]$$

$\sim 10^{13} K_S / \text{yr}$ at LHCb!

The problem is the trigger - with current detector efficiency is very low. Nonetheless…

$$B(K_S^0 \rightarrow \mu^+\mu^-) < 11(9) \times 10^{-9} \text{ at } 90\% (95\%) \text{ CL}$$

This is a topic where LHCb Upgrade will bring big gains.
LHCb $V_{ub}$: possible interpretations

Not only has there been a long-standing inclusive vs exclusive puzzle in $V_{ub}$, but also in $V_{cb}$.

Some commentators * have tried to explain the $V_{ub}$ inclusive vs exclusive puzzle with help of right-handed currents, but the different sensitivity that the baryon result affords disfavours this.

The LHCb result (which is really a $V_{ub}/V_{cb}$ measurement) is suggestive, and also agrees well with the indirect prediction.

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Spectroscopy

Many new states found by LHCb, most of which fit within the ‘vanilla’ quark model

*E.g.* baryons: the discovery of the $\Xi_b^{*-}$ and $\Xi_b^{**-}$ [PRL 114 (2015) 062004]

*E.g.* mesons: first observation of a heavy flavour spin-3 particle [PRL 113 (2014) 162001; PRD 90 (2014) 072003]

\[
m(\Xi_b^{*-}) - m(\Xi_b^{0}) - m(\pi^-) = 3.653 \pm 0.018 \pm 0.006 \text{ MeV}/c^2,
\]

\[
m(\Xi_b^{**-}) - m(\Xi_b^{0}) - m(\pi^-) = 23.96 \pm 0.12 \pm 0.06 \text{ MeV}/c^2,
\]

\[
\Gamma(\Xi_b^{*-}) = 1.65 \pm 0.31 \pm 0.10 \text{ MeV},
\]

\[
\Gamma(\Xi_b^{**-}) < 0.08 \text{ MeV at 95\% C.L.}
\]
EW boson production in forward region

LHCb’s unique forward acceptance means that W and Z (+ low-mass Drell-Yan) production probes two distinct regions of \((x,Q^2)\) space.

The low-\(x\), high-\(Q^2\) region is of particular interest:

- W & Z: \(x \sim 10^{-4}\)
- low-mass Drell-Yan: \(x\) down to \(10^{-6}\)
Impact of LHCb data on PDFs

Look at impact of 2010 LHCb $W \rightarrow \mu \nu$ & $Z \rightarrow e^+e^-$ measurements on HERA-only PDFs

[NNPDF3.0, Maria Ubiali]

Significant impact! But this is of course not including other LHC measurements…

Highlights of LHCb
Erice, Guy Wilkinson
Measurements have been performed of $W \rightarrow \mu \nu$ differential cross-section & charge asymmetry for 2011 data with $E_{\text{CM}}=7$ TeV.

Good agreement with NNLO predictions (using FEWZ) & a variety of PDF sets.

Consistency with CMS (ATLAS too).

Good agreement with NNLO predictions (using FEWZ) & a variety of PDF sets.

Consistency with CMS (ATLAS too).
Impact of 2011 W measurement on PDFs

This measurement [arXiv:1408.4354] provides useful discrimination between PDFs sets...

...and when added into the fits provides significant improvement (now comparing to fit made with HERA and ensemble of all other data)
**Z production (& luminosity measurement)**

\[ pp \rightarrow Z + X \] measurements available in all \( l^+l^- \) modes

Aside – note that LHCb now has most precise luminosity measurement at LHC (indeed, best precision achieved at a bunched hadron collider)

This thanks to beam-gas ‘SMOG’ technique, which complements van der Meer scan measurement

Lumi error = 1.12%

LHCb has also been first to observe \( Z \) production in \( Pb-p \)

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[2014 JINST 9 P12005]

[LHCb-Cong-Conf-2013-0067]

[LHCb-PbPb]
LHCb is an ideal detector for studying $pp \rightarrow p X p$ processes:

- Luminosity ‘just right’ (the Goldilocks experiment)
  - high enough to probe pb x-sections
  - not too high: low pileup (especially with 25 ns running of run 2) makes CEP interactions easy to see

- Acceptance down to $p_T \sim 0$

- Particle identification for hadronic final states

Results already available in 7 TeV exclusive $J/\psi, \psi(2S)$ [JPG 41 (2014) 055002] and full run-1 double $J/\psi$ [JPG 41 (2014) 115002]
High Rapidity Shower Counters for LHCb – HeRSCheL [new for run 2]

System of forward-shower scintillator planes installed in tunnel up to 114 m away from IP to help in definition of forward rapidity gaps. Main physics motivation is Central Exclusive Production.

Five planes, with phototubes and readout optimised for high rate 25 ns operation.

All stations now installed
HeRSChel - early results

Cosmic calibration campaign shows ~170 p.e.s / MIP

Results from beam muons in tunnel (November ‘TED’ tests)

Correlation between stations

Beam pulse from furthest station

Fits perfectly within required interval
Transfer line test (‘TED’)

Sequence of ‘commissioning weeks’, increasing in intensity and focus, intended to wake up detector from hibernation, culminated in transfer line tests of 22-23 Nov.

‘TED’ = stopper at end of transfer line. LHCb profits from resulting muons.

Vibrant atmosphere in control room

All sub-detectors collected useful data

 VELO alignment made with TED data better than 2014 default!

OT drift times

Highlights of LHCb
Erice, Guy Wilkinson

June 2015
Dreaming about ultra-high statistics

Big improvements foreseen before 2018-19 long shutdown (e.g. ~7 fb^{-1} at LHCb, ~ doubling in x-sec from E_{CM} w.r.t. 2012, improved analysis methods) but we can dream of what could be achieved with a very large increase in sample sizes e.g.

- **CKM metrology**
  Determine γ with sub-degree precision to match anticipated improvements in indirect precision coming from lattice QCD. Improve β down to ~0.02°.

- **CPV in B_s mixing**
  Measurement of φ_s with precision much better than SM central value, to probe for sub-leading contributions from NP.

- **B^0_{(s)} \rightarrow \mu\mu**
  True precision measurement of BR down to theory uncertainty and first measurement of ultra-suppressed B^0 \rightarrow \mu\mu BR.

- **B^0 \rightarrow K^*\mu\mu**
  Precision studies of all observables of interest through full angular analysis

- **Charm**
  Extensive study of direct CPV across wide range of modes.
  Sensitivity to indirect CPV down to SM expectation.

Plus great improvements in precision, & *new* measurements, in many other topics!