First LHCb results from pp collisions at 13 TeV

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Outline

- Introduction – LHCb Detector
- Highlights from RUN I
- Real-time detector calibration and alignment
- Enhanced Trigger for RUN II
- Improved tracking
- Selected results from with 13 TeV collision data
- Summary
LHCb Collaboration

- ~ 900 members
- 64 institutes
- 16 countries
- More than 250 published papers!

The Mission

- Precise CPV studies with beauty and charm hadrons
- Rare decays of b and c hadrons
- EW and QCD physics in the forward direction
- Production and spectroscopy in p-p collisions
- Exotica (pentaquarks!)
- Heavy ion data taking
LHCb is dedicated for studying heavy quark flavour physics.

It is a single arm forward spectrometer with pseudo rapidity coverage $2 < \eta < 5$.

Precise tracking system:
- Vertex detector VELO
- Upstream and downstream tracking stations
- 4 Tm warm dipole magnet

Particle identification system:
- RICH detectors
- Calorimeters
- Muon stations

Partial information from calorimeters and muon system contribute to L0 trigger (hardware) that works at LHC clock – 40 MHz.

Full detector readout at 1 MHz.
Although LHCb became a versatile general purpose forward physics experiment its main goal is **precise flavour physics**

- **Complementary** approach w.r.t. Atlas and CMS
  - **Indirect** searches for New Physics using quantum loops

In order to accomplish this we need to **provide**

- superb **tracking** – momentum resolution $\frac{\Delta p}{p} \sim 0.3 - 0.5 \%$
- excellent **vertexing** (primary and secondary) and geometrical **impact parameter** resolutions
- **decay time resolution** $\sim 40 - 50 \, fs$ (depending on the decay mode)
- excellent **PID** (Particle IDentification)
Introduction – LHCb detector

- Tracking system – precise momentum reconstruction, vertexing, decay time resolution
Excellent PID using RICH detectors (cover different momentum range), calorimeters and muon chambers in concert
Performance of the LHCb detector is constantly checked – its performance has a direct impact on physics results

Mass resolution

Performance of the LHCb detector is constantly checked – its performance has a direct impact on physics results.

Decay time

Performance of the LHCb detector is constantly checked – its performance has a direct impact on physics results.

**PID**

[Image of a scatter plot showing Cherenkov angle vs. momentum for different particles (μ, π, k, p) with color coding for efficiency.]

[Image of a graph showing efficiency vs. momentum for different conditions (LL(K - π) > 0, LL(K - π) > 5).]

Highlights from RUN I

Operation conditions of the LHCb in **2011 / 2012**

- **Beam energy** 3.5 / 4.0 [TeV] (15 % increase of the \( b\bar{b} \) x-section)
- Keep the luminosity at \( L_{\text{inst}} = 4.0 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1} \) both years at the constant value by the means of **leveling**
- Average number of **visible interactions** per x-ing slightly higher \( \mu = 1.4 / 1.6 \)
- HLT (High Level Trigger) **input** \( \sim 1.0 \text{ MHz} \), **output** \( \sim 3.0 / 5.0 \text{ kHz} \) (upgraded HLT farm and revisited code)
- **Collected** \( \sim 1.2 / 2.1 \text{ fb}^{-1} \) of collision data
Highlights from RUN I

\[ B^0_{d(s)} \rightarrow \mu^+\mu^- \]

- Full data sample from Run I analysed

\[
\begin{align*}
B(B_s^0 \rightarrow \mu^+\mu^-) &= (2.9^{+1.1}_{-1.0}(\text{stat})^{+0.3}_{-0.1}(\text{syst})) \times 10^{-9}, \\
B(B^0 \rightarrow \mu^+\mu^-) &= (3.7^{+2.4}_{-2.1}(\text{stat})^{+0.6}_{-0.4}(\text{syst})) \times 10^{-10}
\end{align*}
\]


Combined with CMS (joint likelihood fit)

6.2\sigma observation of \( B_s \rightarrow \mu\mu \)
3.0\sigma evidence for \( B_d \rightarrow \mu\mu \)

\[
\begin{align*}
\mathcal{BR}(B_s \rightarrow \mu^+\mu^-) &= 2.8^{+0.7}_{-0.6} \times 10^{-9} \\
\mathcal{BR}(B_d \rightarrow \mu^+\mu^-) &= 3.9^{+1.6}_{-1.4} \times 10^{-10}
\end{align*}
\]

Ratio \( B_s/B_d \) BF’s agreement with SM at 2.3\sigma

(Nature 522 (2015) 68)
Highlights from RUN I

$B^0 \to K^*\mu^+\mu^-$: NP in loops

- Observed forward-backward asymmetry very similar to that predicted by the SM – **world best measurement**
- Cannot clearly state any discrepancy – sample limitation
- New base of observables proposed
- Reduced dependency on hadronic form factors
- Observed discrepancy may be a hint of new heavy neutral $Z'$ particle

$$q_0^2 = 4.9 \pm 0.9 \text{ GeV}/c^2$$
$$q_{0,SM}^2 \in [3.9, 4.4]\text{ GeV}/c^2$$

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[**PRL 111, 191801 (2013)**], new paper summarising Run I results is under way
Lepton universality tests with $B^+ \rightarrow K^+ \ell^+ \ell^-$

- Measured the ratio of branching fractions

$$R_K = \int_{q^2_{\text{min}}}^{q^2_{\text{max}}} \frac{d\Gamma[B^+ \rightarrow K^+ \mu^+ \mu^-]}{dq^2} \int_{q^2_{\text{min}}}^{q^2_{\text{max}}} \frac{d\Gamma[B^+ \rightarrow K^+ e^+ e^-]}{dq^2}$$

- The most precise results to date
- Observed deviation from the SM close to $3\sigma$

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

LHCb:
- Superb performance – greatly exceeded any expectations
- Stable operation at inst. luminosity 100% higher than nominal
- General purpose detector in forward direction
- Many world leading results
- Over 250 papers published!

The SM is standing tall:
- No conclusive BSM physics discovered
- There is still room for NP!
- Need push precision to the limits in order to challenge theoretical predictions
- Some intriguing anomalies (~ $3 - 4 \sigma$) are present
- Need more data to check if this is New Physics looking over our shoulders...
Real-time detector alignment and calibration

- **Novel** approach to on-line trigger system for a HEP experiment
  - Provide **off-line quality** tracking in real-time
  - Need to have robust and reliable procedure for **fill-by-fill calibration and alignment**

- Detector alignment has critical impact on physics performance of the experiment
  - Topological trigger (separation of beauty and charm)

- Momentum resolution $\frac{\Delta p}{p}$
Real-time detector alignment and calibration

- Harsh hadronic environment
- Selection criteria must be tight in order to select required signal samples containing hadronic decays
- Must provide excellent RICH calibration

- **RUN I** (already heavily revised comparing to the original specs)

**Machine**

- **Hardware trigger layer** – **L0**
  - **40 MHz bunch crossing rate**
  - **L0 Hardware Trigger: 1 MHz readout, high E_{T}/P_{T} signatures**
    - 450 kHz h^{+}
    - 400 kHz \(\mu/\mu\)
    - 150 kHz e/\gamma
  - Defer 20% to disk

- **Software trigger layer** – **HLT**
  - **1 MHz full detector read-out**
  - **Data buffer**

- **Storage**

**Software High Level Trigger**
- 29000 Logical CPU cores
- Offline reconstruction tuned to trigger time constraints
- Mixture of exclusive and inclusive selection algorithms

**5 kHz Rate to storage**
Enhanced trigger for RUN II

- **RUN II** (major revision of the trigger system)

**LHCb 2015 Trigger Diagram**

- **Machine**
- **Hardware trigger layer – L0**
- **Splitted – HLT**
- **Storage**

**1 MHz full detector read-out**

- **40 MHz bunch crossing rate**
- **L0 Hardware Trigger**: 1 MHz readout, high $E_T/P_T$ signatures
  - 450 kHz $h^\pm$
  - 400 kHz $\mu/\mu$
  - 150 kHz $e/\gamma$

**Software High Level Trigger**

- Partial event reconstruction, select displaced tracks/vertices and dimuons
- Buffer events to disk, perform online detector calibration and alignment
- Full offline-like event selection, mixture of inclusive and exclusive triggers

**12.5 kHz Rate to storage**
Enhanced trigger for RUN II - alignment

- The procedure uses **tracks reconstructed** in the LHCb tracker and muon stations

- **Iterative** approach
  - Perform reconstruction using the „old” alignment consts.
  - Determine new consts. by global $\chi^2$ minimisation
  - **Repeat** the above till **below** the threshold ($\Delta\chi^2$)

- New set of parameters are ready for HLT2 processing **after several minutes**

- The most sensitive part is the **vertex detector** – new parameters are calculated for **each fill**

- Other tracking detectors much more stable (new consts. needed every few weeks)

- **RICH** mirrors alignment included in this framework
Enhanced trigger for RUN II - calibration

- **RICH** calibration
  - Gas refractive index
  - HPD images distorted due to electric/magnetic field
- Drift time in *gaseous tracking* detectors
  - Mismatch between the LHC and LHCb clocks
- **Calorimeter** calibration
  - Gain equalisation
    - Occupancy method
    - Neutral pion mass position
That’s not all – introducing TURBO
That’s not all – introducing TURBO

- This idea is quite amazing!
- Out of the 12.5 kHz of the output stream ~ 5 kHz is dedicated to the TURBO stream
- The central idea is to save only the trigger level objects that caused it to "fire"
  - Tracks and vertices
  - No raw data is stored for the TURBO
- Huge gain
  - The event size is much smaller
  - No reprocessing
  - Analysis much faster
- Used for high yield exclusive modes (charm)
That’s not all – introducing TURBO

- **The TURBO** stream has been commissioning this year and is performing superbly.
- Below plots obtained directly after the HLT.

- Background almost non existent – tribute for the excellent LHCb tracking performance – off-line tracking quality in the HLT.
- The number of events is much higher than that in RUN I.
Selected results for the RUN II data

- The LHCb detector started to collect data at $\sqrt{s} = 13\ TeV$
- Thanks to excellent performance of the tracking and PID LHCb is well suited for contributing to various QCD tests in the forward direction
  - Unique kinematical coverage at LHC
- Will present cross-section measurements for:
  - prompt $J/\psi$ mesons
  - $J/\psi$ mesons from $b$-hadrons
  - prompt charm mesons
- Previously performed for $\sqrt{s} = 2.76\ TeV, 7\ TeV$ and $8\ TeV$
Selected results for the RUN II data

- **The measurement technique**
  - The double-differential cross-section expressed as a function of the transverse momentum and rapidity:
    \[
    \frac{d^2\sigma_i(H)}{dp_Tdy} = \frac{1}{\Delta p_T \Delta y} \cdot \frac{N_i(H \to f + \text{c.c.})}{\varepsilon_{i,\text{tot}}(H \to f) \cdot \Gamma(H \to f) \cdot \mathcal{L}_{\text{int}}}
    \]
  - Count events $N_i$ decaying to a given final state $f$
  - The main experimental difficulty is to distinguish prompt decays coming from the PV from the secondary signal
    - use pseudo-lifetime for $J/\psi$
    - and impact parameter significance for open charm decays
  - **Luminosity** – precise measurement thanks to the SMOG
    - $\mathcal{L}_{\text{int}}^{J/\psi,b\bar{b}} = (3.05 \pm 0.12) \, pb^{-1}$
    - $\mathcal{L}_{\text{int}}^{c\bar{c}} = (4.98 \pm 0.19) \, pb^{-1}$
Selected results for the RUN II data

- **Signal extraction**
  - $J/\psi$ meson production studied using the $J/\psi \rightarrow \mu^+\mu^-$ decay mode
  - The fraction of $J/\psi$'s originating from b-hadron decays estimated using **pseudo-lifetime** variable

$$t_z = \frac{(z_{J/\psi} - z_{PV}) \cdot M_{J/\psi}}{p_z}$$

- For the charm mesons studies the following decay modes were used: $D^0 \rightarrow K^-\pi^+$, $D^+ \rightarrow K^-\pi^+\pi^+$, $D_s^+ \rightarrow K^-K^+\pi^+$ and $D^{*+} \rightarrow D^0\pi^+$

- Use **impact parameter** significance, $\chi^2_{IP}$, to separate the secondary charm mesons
Selected results for the RUN II data

- **Signal extraction** \( J/\psi \)
  - 2D unbinned extended ML fits for each \( p_T - \gamma \) bin

Separate secondary \( J/\psi \) mesons

Distinguish signal and bkg. by fitting the mass \( m_{\mu^+\mu^-} \)

[arXiv:1509.00771]
Selected results for the RUN II data

- Signal extraction charm
  - Two 1D binned extended ML fits performed simultaneously for all bins

- Separate secondary mesons using $\chi^2_{IP}$

- Separate signal and bkg. by fitting the mass of a given decaying hadron

$D^0 \rightarrow K^- \pi^+$

[ArXiV:1510.01707]
Selected results for the RUN II data

- $J/\psi$ cross-section measurement (prompt and secondary)

\[ \sigma_{\text{prompt}}^{J/\psi} = 15.30 \pm 0.03 \text{ (stat) } \pm 0.86 \text{ (sys) } \mu b \]

\[ \sigma_{J/\psi}^{\text{from } B} = 2.34 \pm 0.01 \text{ (stat) } \pm 0.13 \text{ (sys) } \mu b \]

\[ \sigma^{b\bar{b}} = 515.0 \pm 2.0 \text{ (stat) } \pm 53.0 \text{ (sys) } \mu b \]
Selected results for the RUN II data

- Comparison with theory - $J/\psi$ production
- Cross sections integrated over rapidity - $2 < y < 4.5$

**NRQCD** model for the prompt $J/\psi$ production

[Shao et al., JHEP 1505 (2015) 103]

**FONLL** model for the $b$-hadron $J/\psi$ production

[Cacciari et al., JHEP 1210 (2012) 137]
Selected results for the RUN II data

- Can also compare the results from 13 TeV data sample with the previously measured cross-sections at 8 TeV

NRQCD model for the prompt $J/\psi$ production
[Shao et al., JHEP 1505 (2015) 103]

FONLL model for the b-hadron $J/\psi$ production
[Cacciari et al., JHEP 1210 (2012) 137]
Selected results for the RUN II data

- Charm meson cross-sections

![Graphs showing charm meson cross-sections for D^0 and D^+ particles.](image-url)
Selected results for the RUN II data

- Measured values for respective charm mesons (μb)

\[
\sigma_{D^0}^{prompt} = 3370 \pm 4 \text{ (stat)} \pm 200 \text{ (sys)} \mu b
\]

\[
\sigma_{D^+}^{prompt} = 1290 \pm 8 \text{ (stat)} \pm 190 \text{ (sys)} \mu b
\]

\[
\sigma_{D^+}^{S}^{prompt} = 460 \pm 13 \text{ (stat)} \pm 100 \text{ (sys)} \mu b
\]

\[
\sigma_{D^{*+}}^{prompt} = 880 \pm 5 \text{ (stat)} \pm 140 \text{ (sys)} \mu b
\]

- The integrated cross-sections are given in the LHCb acceptance that is defined as follow
  - rapidity range \(2 < y < 4.5\)
  - transverse momentum of charm meson \(0 < p_T < 8 \text{ GeV}\)
Selected results for the RUN II data

- Evaluate total $c\bar{c}$ production cross-section
- Use fragmentation fractions from electron colliders
- Include $D^0$ and $D^+$ results only ($D_s^*$ and $D^{**+}$ much smaller)

$$\sigma^{c\bar{c}} = 2940 \pm 3\,(\text{stat}) \pm 180\,(\text{sys}) \pm 160\,(\text{frag}) \,\mu b$$
Summary

- First data taken at 13 TeV after the LS1 period
- Updated trigger performs very well
- Measured various cross-sections using new TURBO stream (selection done at the trigger level)
  - prompt $J/\psi$
  - $J/\psi$ from $b$-hadrons
  - total $b\bar{b}$
  - charm mesons $D^0, D^+, D_s^+, D^{*+}$
  - total $c\bar{c}$
- Two papers are under way
  - [LHCb-PAPER-2015-037 for $J/\psi$ and $b\bar{b}$]
  - [LHCb-PAPER-2015-041 $c\bar{c}$]
Back-up
Enhanced trigger for RUN II

- **RUN I** (already heavily revised comparing to the original specs)
- **L0 trigger** (implemented in hardware)
  - Particles with high $p_T$ or $E_T$ measured by the muon system or calorimeters
  - Max output rate $\sim 1.1 \text{ MHz}$ – full event read-out
- **HLT** (High Level Trigger – software implementation)
  - Tunable software platform
  - Run in a huge CPU farm ($\sim 29000$ logical cores)
  - Split into two stages – **HLT1** and **HLT2**
  - HLT1 – L0 decision confirmation
  - HLT2 – inclusive and exclusive selection lines for physics
  - $\sim 20\%$ of L0 data deferred to local disks (data buffer), processing performer during inter-fill gaps
Enhanced trigger for RUN II

- Novel trigger design for RUN II
- L0 part remains virtually the same
- New HLT
- Refreshed filter farm (CPU/disks) and enhanced software allow for off-line quality tracking in real-time!
- Split of the HLT1 and HLT2
  - All data that passed the HLT1 are deferred to disks
  - Quasi real-time detector alignment and calibration before executing the HLT2
- Off-line quality tracking available on-line!
- Contains PID
- No need for time consuming track reprocessing – tracking is done only once by the trigger
Run II and the upgrade road map

- **LHCb**
  - 2014
  - collect 5–7 fb⁻¹

- **LHC LS1**
  - 2015
  - **LHC Run II**
    - *pp* runs 13 TeV @25 ns

- **LHC LS2**
  - 2016–2018
  - collect 15 fb⁻¹

- **LHC LS3**
  - 2019–2023
  - **LHC Run III**
    - *pp* runs 14 TeV @25 ns

- **HL-LHC**
- Single arm spectrometer geometry
- Fully instrumented in rapidity range $2 < \eta < 5$
- Capable of reconstructing backward tracks ($-4 < \eta < -1.5$)
\( B^0 \rightarrow K^*\mu^+\mu^- \): NP in loops

- The largest sample collected
- Clear theoretical quantity
- Sensitive to Wilson coefficients
- World’s best measurement

\( q_0^2 = 4.9 \pm 0.9 \text{ GeV}/c^2 \)

\( q_{0,SM}^2 \in [3.9, 4.4] \text{ GeV}/c^2 \)
Data taking road map for LHCb before the upgrade

LHCb startup  ≈3 fb⁻¹ collected

2010  2011  2012  2013  2014

LHC Run I
- pp runs @50 ns
  - 7 TeV (2010, 2011)
  - 8 TeV (2012)
- Pb Pb run @2.76 TeV
- p Pb run @5 TeV

LHC LS1
- repair splices
- consolidation

2015  2016  2017  2018

collect 5–7 fb⁻¹  Upgrade

LHC Run II
- pp runs 13 TeV @25 ns
- $L_{\text{peak}} \times 10^{34}$ cm⁻² s⁻¹