Introduction to LHCb
Next four lectures:
1. Introduction to LHCb
2. Overview of flavour physics
3. Recent CP violation measurements
4. Recent results from rare decays

Today:
• Starting with some detector physics (bottom-up approach)
• Aimed to give overview of detector aspects important for LHCb
• Assumes some prior knowledge of detector physics....
• …but if I go to fast…..
Please ask questions

If you mated a Bulldog and a Shitzu would it be called Bullshit? 

Not that I know all the answers...
Or if you become bored...

Don’t hesitate to tell me.
The aim of heavy flavour physics is to study $B$ and $D$ decays to look for anomalous effects beyond the Standard Model.

- New particles can appear as virtual particles in loop and penguin diagrams.
- Indirect searches have a high sensitivity to effects from new particles.
  - Can see NP effects before the direct searches.
  - Indirect measurements can access higher scales.
- Possible to measure the phases of the new couplings
  - New physics at TeV scale must have a flavour structure to provide suppression of FCNC.

→ Complementary to direct searches at ATLAS and CMS.
Typical $B$ decay event

- Typical decay length of $B$ hadron $\sim 7$ mm
- Decay products with $p \sim 1 - 200$ GeV
Simulated event

Simulated Event

all

25 ns
LHCb detector

LHCb made for Heavy Flavour physics

• Good vertex resolution
  • Time-dependent measurements.
  • Suppress background from prompt decays.

• Good particle identification
  • Important for trigger, flavour tagging
  • Suppress background.

• Good momentum resolution
  • Mass resolution of heavy flavours.
  • Suppress background.
**Forward detector**

*Why is LHCb not built like ATLAS or CMS?*

Most B (and D) hadrons are produced either in forward or backward direction

→ Due to boost of the $b\bar{b}$ pair
→ $m(b)$ relatively light compared to high centre-of mass energy of LHC

💡 Build LHCb as a forward detector
(backward direction not covered: only one LHCb fits in the cavern 😊)

**Advantages:**
- High yield of B and D hadrons
- Place vertex detector close to beam
- Modular design (easy maintenance)
- Large integrated magnetic field: high momentum resolution.

**Disadvantage**
- Very high particle flux (radiation, reconstruction)

B-hadrons typically fly in the same direction along beam line.
Collaboration

- 760 members
- 15 countries
- 54 institutes

Member countries of the LHCb Collaboration
LHCb in the cavern

- Muon
- Calorimeters
- RICH2
- IT+OT
- Magnet
- TT
- RICH1
- VELO
LHCb setup

Muon

Calorimeters

RICH2

IT+OT

Magnet

TT

RICH1

VELO
B cross section:
- $\sigma_{bb} = 284 \pm 53 \mu b (\sqrt{s} = 7 \text{ TeV})$ [PLB 694 209]

$N_{b\bar{b}} = \sigma_{bb} \int L dt$

→ $3.1 \times 10^{11} b\bar{b}$ pairs already produced at LHCb!

But what does this mean? How many $B$'s are produced?

Cross sections at 14 TeV:

<table>
<thead>
<tr>
<th></th>
<th>Total</th>
<th>Inelastic</th>
<th>$c\bar{c}$</th>
<th>$b\bar{b}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>100 mb</td>
<td>80 mb</td>
<td>3.5 mb</td>
<td>500 $\mu$b</td>
</tr>
</tbody>
</table>

In 1 in every 200 collisions a $b\bar{b}$ pair is produced.
Luminosity

\[ L = \frac{N_1 N_2 n_b f}{4\pi \sigma_x \sigma_y} \]

- Nb. Of protons per bunch for beam 1
- Nb. Of protons per bunch for beam 2
- Nb. Of bunches per beam which participate in the interactions
- Revolution frequency for a single bunch
- Width of the bunches in x, y - direction

\[ \sigma_{x,y} = \sqrt{\beta_{x,y} \varepsilon_{x,y}} \]

- \( \varepsilon \) – emittance (determined by beam quality from pre accelerators)
- \( \beta \) - beta function, i.e. Strength of the focusing magnets

Reminder
Data taking efficiency

- Data taken with high efficiency ~90%
- Offline data quality rejects < 1%
- Sub-detectors all with > 98% active channels.
Pushing LHCb to its limits

Parameters:

- **LHC Beam energy**: Design 7.0 GeV, 2011 3.5 GeV
- **Number of bunches in LHC**: Design 2808, 2011 1300
- **Number of interactions per BX**: Design 0.5, 2011 1.5
- **Instantaneous luminosity**: Design 2.0 $10^{32}$ cm$^{-2}$s$^{-1}$, 2011 $10^2$ µb$^{-1}$s$^{-1}$
- **Running time**: Design $10^7$ seconds, 2011 $0.4*10^7$ seconds
- **Integrated luminosity per year**: Design 2.0 fb$^{-1}$, 2011 1.1 fb$^{-1}$

Performance of LHC in 2011

- Lower beam energy: b cross section only half.
- Fewer number of bunches
- Effective running time LHC in 2011 only 1.5 month.

Solution LHCb:

- Run at higher instantaneous luminosity
  → Trigger and reconstruction must cope with higher multiplicities
- Luminosity leveling (see next slide)
Luminosity leveling

- LHCb already running above design lumi
  - Average $L \sim 3 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$ (nominal $2 \times 10^{32}$)
- Need to cope with higher occupancies
  - More pile-up: average $\mu \sim 1.5$ (nominal 0.5)
- Continuous, automatic adjustment of offset of colliding beams.
- Allows optimal conditions throughout a fill.
- Very new technique. Not all LHC experts were convinced it would work.
- Allows to take data much more efficiently.
Follow actual status on “LHC page 1”
## LHCb from a tracking point of view

<table>
<thead>
<tr>
<th>Goal</th>
<th>Purpose</th>
<th>Solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Measure <strong>proper time</strong> of decaying particles</td>
<td>Identify $B$ hadrons and time-dependent analysis.</td>
<td>Vertex detector: <strong>VELO</strong> (+tracking stations)</td>
</tr>
<tr>
<td>2. Measure <strong>mass</strong> of decaying particles</td>
<td>Identify signal and separate from background.</td>
<td>Magnet + tracking stations: <strong>TT, IT, OT</strong> (+<strong>VELO</strong>).</td>
</tr>
</tbody>
</table>

LHCb has extremely good mass and proper time resolution.
Vertex detector

- Two retractable halves.
- 21 modules, each with a $r$- and $\phi$-measuring sensor.
- Strip pitch: 36–102 $\mu$m.
- S/N > 20
(Reminder) Silicon detectors

- Bias voltage between backplane and strips.
- Bias voltage such that silicon is depleted of charge carriers (depletion voltage).
- Traversing charged particle creates electron-hole pairs.
- Holes and electrons generated along path (only showing holes)
- Holes attracted by strips, electrons by the backplane.
Vertex reconstruction

\[ B_s \rightarrow D_s(K K \pi) \pi \]

\[ \langle L \rangle = 7 \text{mm} \]

\[ L = c \beta \gamma t \]

\[ t = \frac{Lm}{p} \]

Proper time resolution

\[ \sigma \sim 42 \text{ fs} \]
**Vertex reconstruction**

- VELO sensors only 8 mm from beam.
- Impact parameter resolution = 12 $\mu$m for high $p_T$ tracks.
- Good primary and secondary vertex resolution.
  - Suppress background from prompt decays.
- Good proper-time resolution
  - Important for time-dependent measurements.

**VELO “tomography” with vertices from secondary interactions with material**

- RF foil must be as thin as possible to reduce error on the vertex position.
- In good agreement with simulation.
Vertex reconstruction

Primary vertex resolution

for 25 tracks:
\[ \sigma_x \approx 16 \, \mu m \]
\[ \sigma_y \approx 16 \, \mu m \]
\[ \sigma_z \approx 76 \, \mu m \]

LHCb VELO Preliminary
\( \sqrt{s} = 7 \, \text{TeV Data} \)

Decay time in \( B_s \to J/\psi \phi \)

Resolution from prompt \( J/\psi \): \( \sigma_t = 50 \, \text{fs} \)

LHCb Preliminary
\( \sqrt{s} = 7 \, \text{TeV, } L = 337 \, \text{pb}^{-1} \)
Magnet

Tracking system and dipole magnet to measure angles and momenta

$\Delta p/p \sim 0.4\%$, mass resolution $\sim 14$ MeV (for $B_s \rightarrow D_s K$)
Tracking system: TT

- Just after RICH1 and before the magnet
- Four layers (0°, +5°, −5°, 0°) of 150 x 130 cm.
- Strip pitch: 183 µm.
- S/N ~ 13
- 64 modules with 14 sensors each.
- Hit resolution about 50 µm.
Tracking system: TT

→ TT needed to compensate scattering of RICH1.
→ Improves mass resolution by about 25-30%.
T stations

Why do the tracking stations after the magnet consist of two detectors?
Tracking system: IT

- 3 stations with 4 boxes each.
- Each box has 4 layers (0°, +5°, −5°, 0°).
- Strip pitch: 198 µm.
- S/N ~ 16
- Hit resolution about 50 µm.

Inner Tracker: Silicon sensors

264 Module
Tracking system: OT

- 3 stations of modules with straw tubes
- Each station has 4 layers (0°, +5°, −5°, 0°).
- Straw pitch: 5 mm
- Resolution: ~200 micron
Tracking system: OT

Module cross section

340 mm

31 mm

Panels

Cathode straw

Anode wire

5.0 mm

5.5 mm

5.25 mm
Tracking system: Outer Tracker

Straw tube drift chamber modules

5mm cells
pitch 5.25 mm

Track

Cathode

Kapton 100\textmu{}m
Aluminium 12.5\textmu{}m
Kapton 160\textmu{}m
adhesive 10\textmu{}m
adhesive 15\textmu{}m

2.5 m
Outer Tracker
Track reconstruction

Average # of tracks in b-events:
- 34 VELO,
- 33 long,
- 19 T tracks,
- 6 upstream,
- 14 downstream

Total 106 reconstructed tracks
Track reconstruction

Why should the tracking detectors be light?

Reason 1: Otherwise they will stop the particles (hadronic showers)

- Thickness of material in tracking system: 18% (over 9m of distance)
- That means ~18% of the hadrons have hadronic interaction (shower) in detector.
- Hadronic interactions only important for hadrons (muons and electrons not affected).

18% thickness corresponds to 8 cm of aluminium
Track fitting

**Definition (Merriam-Webster)**
Track [trak]: Detectable evidence (as the wake of a ship, a line of footprints, or a wheel rut) that something has passed.

**Definition (High-energy physics)**
Path of a **charged particle** through a detector.

Track is a collection of **track states** along this path
→ conveniently parameterized in z positions (LHCb).

**Track state:**
• State vector

\[
\vec{x} = \begin{pmatrix}
x \\
y \\
t_x \\
t_y \\
q/p
\end{pmatrix}
\]

at a given z-position, where \( t_x = \frac{\partial x}{\partial z} \) and \( t_y = \frac{\partial y}{\partial z} \).

• Plus corresponding covariance matrix (5x5).
Track fitting

Track fit issues:
• Many parameters.
  • $5n$ free parameters ($n =$ number of states)
• Need to incorporate material effects (see below)
  • More free parameters to fit

Solution
• Run track fit recursively: add measurements one by one. Fit only the state at the current measurement.
→ This is the Kalman filter.

Two material effects included in stepping through matter:
1. Energy loss
2. Multiple scattering
Track fitting

\[ \tilde{x}_{k+1}^{k} \rightarrow \tilde{x}_{k+1} \rightarrow m_{k+1} \rightarrow \tilde{x}_{k} \rightarrow \tilde{x}_{k-1} \rightarrow m_{k} \rightarrow \tilde{x}_{k-1} \rightarrow m_{k-1} \]

true trajectory

Material layer

- **x**: track states
- **m**: measurements
Material effects in track fit

1. **Energy loss** (all charged particles except electrons)
   - Caused by ionization of the medium.
   - Note that this effect is actually needed to measure the particles (hits)!

Uses Bethe Bloch formula (depends on density, thickness, and Z/A)

\[
\frac{dE}{dx} = 4\pi N_A r_e^2 m_e c^2 Z \frac{1}{A} \left[ \frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 T_{\text{max}}}{(1 - \beta^2) I^2} - \beta^2 - \frac{\delta}{2} \right]
\]

- MIP loses about 40 MeV in 8 cm of aluminium: small effect in the LHCb tracking system (typical momentum is 2-200 GeV).
- But still larger than momentum resolution (10-30 MeV).
Electrons and photons

**Electrons**

- Electrons lose their energy not by ionization but by bremsstrahlung.
- For bremsstrahlung energy loss is inversely proportional to mass of particle.
- Electrons lose 30% of their energy before magnet due to bremsstrahlung:

\[
- \frac{dE}{dx} = \frac{E}{X_0}
\]

Radiation length: In LHCb about 60% in tracking system.

- Therefore, momentum (and mass) resolution worse compared to muons

**Photons**

- Related to bremsstrahlung is photon conversion \( \gamma \rightarrow e^+ e^- \)
- Mean free path is \( 7/9 X_0 \)
- Converted photons before the magnet cannot be reconstructed.
  - After magnet they still form single cluster in calorimeters.
Material effects in track fit

Why should the tracking detectors be light?

Reason 2: Otherwise they will scatter more (worse momentum resolution)

2. Multiple scattering
   - Modeled by increasing covariance (error) matrix (not predictive).
   - Uses Molière angular distribution: depends mainly on momentum, density, thickness.
   - Significant effect for low momentum particles (depends on spatial resolution)
     - In case of LHCb: particles below $p < 80$ GeV.

Multiple scattering (Moliere angular distribution):

$$
\theta_0 = \frac{13.6 \text{ MeV}}{\beta c p} z \sqrt{\frac{x}{X_0}} \left[ 1 + 0.038 \ln \frac{x}{X_0} \right]
$$

Thickness/radiation length: taken from detector description (simulation)
Momentum resolution

- Integrated Bdl $\sim 4 \text{Tm}$
- Accurate field map and alignment
- Momentum resolution 0.4-0.6 %
- Mass resolution $J/\psi$: 13 MeV
  - MC: 10 MeV
→ Accurate mass measurements.
Momentum resolution

The momentum kick from the magnet (~1 GeV) depends on integrated magnetic field:

$$\Delta \vec{p} = q \int d\vec{l} \times \vec{B}$$

The main component can be written as

$$\Delta p_x = p_{x,f} - p_{x,i} = p \left( \frac{t_{x,f}}{\sqrt{1 + t_{x,f}^2 + t_{y,f}^2}} - \frac{t_{x,i}}{\sqrt{1 + t_{x,i}^2 + t_{y,i}^2}} \right) = q \int \left| d\vec{l} \times \vec{B} \right|_x$$

Where $t_x$ is the slope (dx/dz) of the particle.

Using the multiple scattering formula and the expected hit resolution one obtains the following parameterization:

$$\frac{\partial p}{p} = A \oplus B \cdot p$$

Very simplified model. In particular it does not describe:
- different resolutions of IT and OT
- different amounts of material seen by different particles
- non-Gaussian effects
Invariant mass

Invariant mass formula (2 body decay):

\[ m_M^2 = m_1^2 + m_2^2 + 2(\sqrt{p_1^2 + m_1^2} \sqrt{p_2^2 + m_2^2} - |\vec{p}_1| |\vec{p}_2| \cos \Theta) \]

Assuming \( m_{1,2} \ll p_{1,2} \)

\[ m_M^2 = m_1^2 + m_2^2 + 2|\vec{p}_1||\vec{p}_2|(1 - \cos \Theta) \]

Opening angle term

In LHCb error on opening angle term typically much smaller than momentum error.

Mass resolution mainly determined by momentum resolution
Full mass spectrum
Measurement of $B$ masses

LHCb-CONF-2011-027: B masses [MeV/c²]

<table>
<thead>
<tr>
<th>Decay</th>
<th>MeV/c²</th>
<th>PDG</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M(B^+ \to J/\psi K^+)$</td>
<td>5279.27 ± 0.11 (stat) ± 0.20 (syst)</td>
<td>5279.17 ± 0.29</td>
</tr>
<tr>
<td>$M(B^0 \to J/\psi K^{*0})$</td>
<td>5279.54 ± 0.15 (stat) ± 0.16 (syst)</td>
<td>5279.50 ± 0.30</td>
</tr>
<tr>
<td>$M(B^0 \to J/\psi K^0_S)$</td>
<td>5279.61 ± 0.29 (stat) ± 0.20 (syst)</td>
<td>5279.50 ± 0.30</td>
</tr>
<tr>
<td>$M(B^+_s \to J/\psi \phi)$</td>
<td>5366.60 ± 0.28 (stat) ± 0.21 (syst)</td>
<td>5366.30 ± 0.60</td>
</tr>
<tr>
<td>$M(\Lambda_b \to J/\psi \Lambda)$</td>
<td>5619.49 ± 0.70 (stat) ± 0.19 (syst)</td>
<td>5620.2 ± 1.6</td>
</tr>
<tr>
<td>$M(B^+_c \to J/\psi \pi^+)$</td>
<td>6268.0 ± 4.0 (stat) ± 0.6 (syst)</td>
<td>6277 ± 6</td>
</tr>
</tbody>
</table>

More precise than PDG values!

World-best mass measurements! (2010 data only)
Particle ID

Which particles travel through LHCb?

- Electrons ($e^+$, $e^-$)
- Muons ($\mu^+$, $\mu^-$)
- Photons (neutral; detected in calorimeter)
- Pions ($\pi^+$, $\pi^-$)
- Kaons ($K^+$, $K^-$, $K_S^0$ decays after 2 m in $\pi\pi$)
- Protons ($p^+$, $p^-$)
- Neutrons (neutral; detected in calorimeters)
- Lambda’s (neutral; decay after ~2m into $p\pi$)
- + small fraction of other long-lived strange baryons

PID detectors used to separate the different species.
Note that the tracking detector only detect charged particles!
Two RICH detectors for charged hadron identification
RICH detectors are the specialized detectors to allow charged hadron ($\pi$, K, p) identification.

Important for B physics, as there are many hadronic decay modes e.g.: $B_s \rightarrow D_s^- K^+ \rightarrow (K^+ K^- \pi^+) K^+$

\[
\cos \theta_c = \frac{1}{(\beta n)}
\]

Radio Imaging

\[
\text{Ring radius} \rightarrow \theta_c \rightarrow \beta
\]
RICH detectors

RICH 1

RICH 2

Radiator:
Aerogel \( n = 1.03 \)
\( \text{C}_4\text{F}_{10} \) \( n = 1.0014 \)

Radiator: \( \text{CF}_4 \) \( n = 1.0005 \)

3 radiators to cover full momentum range

\( \theta_{c, \text{max}} = 242 \text{ mrad} \)
RICH detectors

RICH 1

RICH 2

Radiator: Aerogel $n=1.03$
C$_4$F$_{10}$ $n=1.0014$

Radiator: CF$_4$
$n=1.0005$

$\varepsilon (K \rightarrow K) = 88\%$

$\varepsilon (\pi \rightarrow K) = 3\%$

$\pi \rightarrow K$

Momentum (GeV/c)

Efficiency (%)
RICH performance

**No RICH**

\[ B_s \rightarrow K K \]

- purity 13%

\[ B_s \rightarrow D_s K \]

- purity 7%

**With RICH**

\[ B_s \rightarrow K K \]

- purity 84%
- efficiency 79%

\[ B_s \rightarrow D_s K \]

- purity 67%
- efficiency 89%
**Calorimeter system** to identify electrons, hadrons and neutrals. Important for the first level (Level 0) of the trigger.
Muon system to identify muons, also used in first level (L0) of the trigger
Calorimeters and Muon detectors

Calorimeters:
- Goal is to stop the particles and measure their energy (heavy detectors).
- Particles produce shower of secondary particles.
- Amount of scintillation light is measure for energy of incoming particle.
- Electrons and photons give electromagnetic shower in first part of calorimeters: ECAL
- Hadrons give hadronic shower in second part of calorimeters: HCAL
- Calorimeter is only place where neutral particles are detected.

Muon detectors:
- Muons are not so much affected by material in calorimeters.
  - They cannot have hadronic interaction, only electromagnetic.
- Muon detectors interleaved with iron wall to remove any non-muon.
- Anything that traverses through the muon detector must be a muon.
**PID performance: flavour tagging**

**Flavour tagging**
- Tagging of production flavour (B or $\bar{B}$)
- Important for mixing & CP analyses.
- Performance calibrated using control channels such as $B^+ \rightarrow J/\psi K^+$
- Tagging power: $\varepsilon(1-2\omega)^2 =$
  - $(3.2 \pm 0.8)\%$ (opposite-side tag)
  - $(1.3 \pm 0.4)\%$ (same-side tag)
from $B_s \rightarrow D_s \pi$ mixing analysis.
Trigger: Level-0 trigger

Calorimeter
Muon system
Pile-up system

40 MHz

**Level-0 Hardware:** (4μs)
High $p_T$, $\mu$, $e$, $h$, $\gamma$ signatures
1.1, 2.8, 3.6, 2.6 GeV

1 MHz

**PC Farm:**
Higher Level Trigger
(full event info)
Hardware Level-0 trigger followed by two-stage software High Level Trigger, HLT1 and HLT2

- HLT1 performs partial reconstruction, confirms L0 objects: associates them with reconstructed tracks, especially with those displaced from the PV
- HLT2: full reconstruction; uses reconstructed objects for exclusive selections with clear signature

Depending on luminosity, the L0 and HLT thresholds can be tuned such that not to exceed maximal throughput of the systems.

Average event size ~35 kB
Trigger: High-level trigger

Higher Level Trigger (Software)
Stepwise event reconstruction:
- Confirmation of trigger signature using tracking chambers
- Secondary vertex reconstruction
- Full event reconstruction

2 KHz Storage (event size ~ 50 kB)

<table>
<thead>
<tr>
<th>HLT rate</th>
<th>Event type</th>
<th>Calibration</th>
<th>Physics</th>
</tr>
</thead>
<tbody>
<tr>
<td>200 Hz</td>
<td>Exclusive B candidates</td>
<td>Tagging</td>
<td>B (core program)</td>
</tr>
<tr>
<td>600 Hz</td>
<td>High mass di-muons</td>
<td>Tracking</td>
<td>J/ψ, b→J/ψX (unbiased)</td>
</tr>
<tr>
<td>300 Hz</td>
<td>D* candidates</td>
<td>PID</td>
<td>Charm (mixing &amp; CPV)</td>
</tr>
<tr>
<td>900 Hz</td>
<td>Inclusive b (e.g. b→μ)</td>
<td>Trigger</td>
<td>B (data mining)</td>
</tr>
</tbody>
</table>
LHCb Upgrade

- Main limitation that prevents exploiting higher luminosity is the Level-0 (hardware) trigger

- To keep output rate < 1 MHz requires raising thresholds → hadronic yields reach plateau

- Proposed upgrade is to remove hardware trigger read out detector at 40 MHz (bunch crossing rate) Trigger fully in software in CPU farm.

- Will allow to increase luminosity by factor ~ 5 to 1–2 × 10^{33} cm^{-2} s^{-1}

- Requires replacing front-end electronics and part of tracking system. Planned for the long shutdown in 2018. Running for 10 years will then give ~ 50 fb^{-1}

- Letter of Intent recently submitted to the LHCC Physics case endorsed, detector R&D underway (e.g. scintillating-fibre tracking, TOF, …)
I think we've got enough information now, don't you?

All we have is one "fact" you made up.

That's plenty. By the time we add an introduction, a few illustrations, and a conclusion, it will look like a graduate thesis.
Conclusion

• LHCb has just collected 1.1 fb$^{-1}$ of data.
• Waiting for you to be analysed!