Introduction to the LHCb masterclass exercise

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You will all have received a printout with instructions for the workshop. Here I will

Briefly motivate why these exercises are interesting

Explain what the LHCb detector is

Explain the data format

Give you some starting point for performing the exercises
What will you be measuring today?
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The object of this exercise is for you to measure the lifetime of a certain kind of particle found in nature.
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The object of this exercise is for you to measure the lifetime of a certain kind of particle found in nature.
What kind of particles are there?

There are a small number of fundamental particles.
Smaller than atoms...

If the proton and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.
What kind of particles are there?

There are a small number of fundamental particles. And a massive number of composite particles made up of quarks! The above is nowhere near the full list!
What kind of particles are there?

The monks had their bible...
The monks had their bible... We have the Particle Listings!
What do quarks form?

Two different kinds of combinations: quark–antiquark, or three (anti)quarks. Antiparticles have opposite charges to the corresponding particles, but are otherwise supposed to interact in the same way. Most particles have a corresponding antiparticle (but sometimes a particle is its own antiparticle).
What are some typical particle lifetimes?

<table>
<thead>
<tr>
<th>Type</th>
<th>Name</th>
<th>Symbol</th>
<th>Energy (MeV)</th>
<th>Mean lifetime</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lepton</td>
<td>Electron / Positron</td>
<td>$e^- / e^+$</td>
<td>0.511</td>
<td>$&gt; 4.6 \times 10^{26}$ years</td>
</tr>
<tr>
<td></td>
<td>Muon / Antimuon</td>
<td>$\mu^- / \mu^+$</td>
<td>105.7</td>
<td>$2.2 \times 10^{-6}$ seconds</td>
</tr>
<tr>
<td></td>
<td>Tau lepton / Antitau</td>
<td>$\tau^- / \tau^+$</td>
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<td>$2.9 \times 10^{-13}$ seconds</td>
</tr>
<tr>
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<tr>
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<td></td>
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<tr>
<td>Boson</td>
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<td>$W^+ / W^-$</td>
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Wikipedia: can’t live with it, can’t live without it...
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A huge range of different lifetimes: you will be measuring a pretty short one...

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How do we measure a short lifetime?

As an example, consider a particle which lives $10^{-12}$ seconds.
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$t' = t/\sqrt{1-v^2/c^2}$

Typically an LHC particle with a lifetime of $10^{-12}$ seconds will fly 1 cm... that is long enough that we can measure it!
So why is the $D^0$ special?

$D^0$ meson

Charm quark

Up antiquark
So why is the $D^0$ special?

$D^0$ meson

Charm antiquark

Up quark
So why is the $D^0$ special?

$D^0$ meson

Charm quark  Up antiquark
It oscillates!

The $D^0$ is a neutral particle: it can oscillate between matter and antimatter before decaying!
Why does antimatter matter?
Equal amount of matter and antimatter created.
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Equal amount of matter and antimatter created.

Afterglow Light Pattern 400,000 yrs.

Dark Ages

Development of Galaxies, Planets, etc.

Inflation

Quantum Fluctuations

1st Stars about 400 million yrs.

Big Bang Expansion 13.7 billion years

Dark Energy Accelerated Expansion

Today: almost no antimatter in the universe
Why does antimatter matter?

Equal amount of matter and antimatter created

Today: almost no antimatter in the universe

So where did all the antimatter go?
It oscillates!

The $D^0$ is a neutral particle: it can oscillate between matter and antimatter before decaying! Such particles can give us insight into small differences between matter and antimatter.
Why the $D^0$ and not another particle?

Neutral mesons can oscillate between matter and anti-matter as they propagate.
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Classic example is the $B_d$ meson: measurement of $B_d$ oscillations was an early indication of the top quark mass.
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Oscillations are interesting because they are sensitive to new particles appearing virtually inside the box diagram, which can be very much heavier than directly produced particles.
Why the $D^0$ and not another particle?

Neutral mesons can oscillate between matter and anti-matter as they propagate.

There are several different "down-type" mesons which oscillate: $(ds) \ K^0$, $(db) \ B_d$, $(sb) \ B_s$

But only one up-type: the $(cu) \ D^0$ meson

The top quark does not form mesons or baryons

This makes the $D^0$ a unique laboratory for studying matter-antimatter symmetry in the up-type quark sector.
Large hadron collider @ CERN

Start the protons out here
Large hadron collider @ CERN
Large hadron collider @ CERN
Large hadron collider @ CERN
Protons colliding…
Protons colliding...
Protons colliding…
Protons colliding...
$p_T = \text{Transverse momentum}$

$E_T = \text{Transverse energy}$
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LHCb @ LHC

- ELECTRONS
- PHOTONS
- HADRONS

$p_T$ = Transverse momentum
$E_T$ = Transverse energy
**LHCb @ LHC**

- **ELECTRONS**
- **PHOTONS**
- **HADRONS**
- **MUONS**

$p_T = \text{Transverse momentum}$

$E_T = \text{Transverse energy}$
LHCb and CMS geometries compared

\[ p_T = \text{Transverse momentum} \]
\[ E_T = \text{Transverse energy} \]
LHCB performance

$\sigma_{\text{eff}} / t = 4.5 \times 10^{-14}$ s

$LHCb$ performance

$X$ and $Y$ resolution - offline, exactly 1 PV

\[ \chi^2 / \text{ndf} = 59.8 / 33 \]
Prob: 0.002913

$X$ - Const: 0.1061 ± 0.009001
Power: 0.6666 ± 0.0666

$Y$ - Const: 0.1164 ± 0.0121
Power: 0.7526 ± 0.07157
Epsilon: 0.0004835 ± 0.001658

$LHCb$ VELO Preliminary
\( \sqrt{s} = 7 \text{ TeV} \) 2011 Data

Event/0.05 ps

$LHCb$ Preliminary
\( \sqrt{s} = 7 \text{ TeV} \)
LHCb performance

We can measure lifetimes down to a few times $\sim 10^{-14}$ seconds...
10% of LHC interactions produce a charm hadron: LHCb has already collected more than 1 billion signal charm decays!
How sensitive is my measurement?

This is not an absolute rule but...

If you have no background and you have collected \( N \) signal events, then you can measure properties related to the signal production and decay (this includes the lifetime) with a relative precision of \((100/\sqrt{N})\%

\[
\begin{array}{lcl}
100 & \text{events means 10.0\% precision} \\
10000 & \text{events means 1.00\% precision} \\
1000000 & \text{events means 0.10\% precision} \\
100000000 & \text{events means 0.01\% precision}
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LHCb IS HERE
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<td>1000000</td>
<td>0.10%</td>
</tr>
<tr>
<td>100000000</td>
<td>0.01%</td>
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LHCb IS HERE

So we can’t give you the full dataset to use!

WORLD PRECISION IS 0.35%
The purpose of this exercise is to

- Give you a look at the data coming out of the LHC
- Teach you about selecting particles in the LHC data
- Teach you about fitting functions to the data in order to measure the signal properties
- Teach you about systematic uncertainties in measurements
Use $D^0 \to K\pi$ events from 2012 datataking, starting mass distribution above.
Because LHCb is a forward spectrometer with a dipole magnet, it is hard to do visual exercises looking at the full detector. Hence we zoom in around the interaction region for you to find displaced vertices.
The visual analysis framework
An “easy” event
A “harder” event
An example histogram
Once you finish looking for the events, you will get a bigger collection of data to use in order to measure the lifetime.
As with the event display, there are online instructions
Fitting the mass

Your first task is to fit functions to signal and background
Now use that fit to plot the distributions of background and signal events in the other physical parameters.
Plotting the distributions

And fit the lifetime! Does your result agree with slide 51?