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Upgrading the LHCb Masterclass Exercise: Measuring the D^0 Meson Lifetime

Arbesa BERISHA, UNIVERSITY OF PRISHTINA

Supervisors: Ben COUTURIER
Sebastien PONCE
Gediminas SARPIS

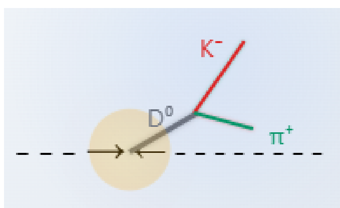
Abstract

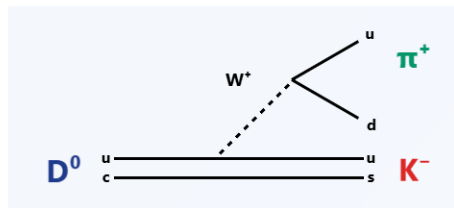
This project upgrades the LHCb Masterclass exercise for measuring the D^0 meson lifetime. The old version has been replaced with a modern browser-based application that uses updated 2024 proton–proton collision data from the LHCb detector. The new interface offers improved data visualisation, interactive selection tools, helping students explore how analysis choices affect the measured lifetime. These enhancements make the exercise more modern, accessible, and engaging, giving users an experience closer to real particle physics analysis.

1 What is the LHCb masterclass?

The LHCb Masterclass [1] is a one-day educational event where high-school students analyze real collision data from the LHCb detector at CERN's Large Hadron Collider. Main Activities:

1. **Event Display Exercise** - Students use an interactive event display tool to examine real particle collisions recorded by the LHCb detector. The goal is to identify pairs of particle tracks corresponding to the decay of a D^0 meson into a kaon and a pion.





They look for displaced vertices—places where the D^0 meson decays some distance away from the primary proton-proton collision. By selecting one kaon track and one pion track from such vertices, students form candidate pairs. The invariant mass of these pairs,

$$m(K\pi) = \sqrt{(E_K + E_\pi)^2 - (\vec{p}_K + \vec{p}_\pi)^2}$$

is calculated and added to a histogram, where E_K and E_π are the energies, and $\vec{p}_K$ and $\vec{p}_\pi$ are the momenta of the kaon and pion, respectively. Only pairs with mass values within the expected signal range of about 1815 to 1915 MeV are accepted. The invariant mass values are collected into this histogram, where the $x-$axis represents the invariant mass of kaon-pion pairs and the $y-$axis shows the number of candidate pairs for each mass bin. This histogram typically displays a pronounced peak within the 1815 to 1915 MeV range, corresponding to the D^0 meson signal, above a background of random combinations. This process builds up the D^0 mass distribution in the histogram [7].

2. **Measuring the D^0 Lifetime** - The software fits a Gaussian (normal) distribution to the invariant mass data to identify the D^0 signal peak ($\sim$1865 MeV). Students select events within a signal window defined by

mass values typically between 1810 and 1915 MeV to ensure a sample for further analysis. Using this selected sample, they measure the lifetime of the D^0 meson by fitting the decay-time distribution, which follows an exponential decay pattern.

Key variables used in this measurement are:

- D^0 Mass: The invariant mass of the kaon-pion pair, showing a signal peak between roughly 1810 and 1915 MeV.
- D^0 Lifetime (τ): Determined by fitting the exponential decay of the selected candidates within the signal window. The accepted values of decay times are typically bounded between about 0.25 ps and 10 ps.
- Impact Parameter (IP): The closest distance between the D^0 trajectory and the original collision point; smaller IP values indicate the particle likely originated directly from the primary vertex.
- Transverse Momentum (PT): The component of the particle's momentum perpendicular to the LHC beamline, which is important for event selection and typically varies between 2.4 GeV/c and 20 GeV/c in the analysis.

For context, the world-average lifetime of the D^0 meson, as provided by the Particle Data Group, is about 410 femtoseconds (fs) or 0.410 picoseconds (ps) [8]. The Masterclass exercise allows students to estimate this lifetime from real data collected at the Large Hadron Collider beauty experiment (LHCb) [3], which is one of the major detectors at the LHC, the world's largest proton-proton collider [2].

2 Why we updated the LHCb masterclass?

Since 2005, International Masterclasses [4] have given high-school students aged 16–19 the chance to discover particle physics by working with real experimental data. This has brought the abstract ideas of modern physics closer to everyday life and helped students understand how scientific research is done.

Today, each year over 13,000 high-school students from 60 countries step out of the classroom for a day to immerse themselves in the world of quarks and leptons. Hosted by 225 universities and research centres, these masterclasses give participants a unique opportunity to perform measurements on real data from particle physics experiments, thereby experiencing the work of researchers first-hand.

Since 2013, the LHCb Masterclass has been part of the International Masterclasses, giving high-school students the opportunity to work specifically with data from the LHCb experiment. However, the LHCb Masterclass materials and datasets have not been updated since 2019. Besides updating the data, it was necessary to improve the web platform itself, making it more attractive and user-friendly, with a better visual presentation of the experiment and its results.

3 Upgrade implementation

I worked on updating the D^0 lifetime measurement exercise as part of a project to modernize the LHCb Masterclass. This exercise runs through a web application that gives students a hands-on way to measure the lifetime of D^0 mesons. With an event display tool, students can look at LHCb collision events where D^0 mesons decay and use filters and analysis tools to find important physics results.

The aim of the upgrade was to replace the old D^0 mass measurement interface with a new Python-based version that runs directly in the browser (built with PyScript 2025.7.3 [5]) and to add better visual features. At the same time, another team member created a new event display using the HSF Phoenix library.

Now, the main page has been redesigned to be clearer and easier to use. First, students enter their institution name and pick one of fifteen datasets to study. On the right side of the screen, there are three main sections:

- Introduction – a short overview of the exercise, explaining the goals and the steps before students start.
- Event Display – a visual tool (built with HSF Phoenix) for spotting kaon–pion decay events from secondary collision points.
- Measuring the D^0 Lifetime – where students analyse the recorded event data, apply selection criteria to isolate a reliable set of decay candidates, and use it to measure the D^0 meson lifetime.

3.1 The analysis process

This exercise uses 2024 proton–proton collision data recorded by the LHCb detector. The objective is to measure the lifetime of the D^0 meson through a clearly defined analysis chain implemented in Python and executed in the upgraded browser-based environment. The workflow moves from identifying the signal in the invariant mass spectrum, through selection and background subtraction, to extracting the lifetime via exponential fitting.

The invariant mass distribution is modeled using a Gaussian function to describe the D^0 signal peak and a constant term to represent the flat combinatorial background, as given by:

$$G(x) = b + a \cdot \exp\left(-\frac{(x - x_0)^2}{2\sigma^2}\right)$$

In this model, a is the height of the signal peak, x_0 is the known D^0 mass position, σ is the width of the peak related to detector resolution, and b is the constant background level. The fit is performed using `scipy.optimize.curve_fit` [6]. After mass filtering, the dataset is further refined by applying cuts on PT, TAU and logIP.

These cuts are applied as Boolean masks over the event arrays. The values are controlled through HTML/JavaScript sliders in the web UI, which trigger immediate re-computation of all subsequent plots by re-running the `NumPy` filtering pipeline. This design enables students to interactively explore how each variable affects both the signal yield and background.

Even though the LHC produces many charm particles, it also generates a larger number of other particles that can mimic the signal ("backgrounds"). To extract meaningful information from such large candidate samples, excellent control over these backgrounds is essential. A common method called background subtraction estimates the combinatorial background from sidebands of the mass distribution, rescales it to match the expected background level in the signal region, and then subtracts it from the observed yield. The scaling factor is calculated as the ratio of background yield under the signal peak (from the fit) to the sideband event count:

$$\text{Scale} = \frac{\text{Background under peak (fit)}}{\text{Background in sideband}}$$

The scaled sideband histogram is then subtracted bin-by-bin from the signal-window histogram, yielding the background-subtracted "pure signal" distribution, which can be expressed as:

$$\text{Pure signal } = \text{Raw Signal} - (\text{Scale} \times \text{Background})$$

This procedure is applied similarly to each variable: PT, TAU and $\log \text{IP}$.

The decay time histogram after background subtraction is fitted with the exponential decay model:

$$D(t) = A \cdot \exp\left(-\frac{t}{\tau}\right)$$

where A is the number of events at $t = 0$ and τ is the lifetime of the D^0 mesone. The uncertainty (standard error) on τ is extracted as:

$$\sigma_\tau = \sqrt{\text{pcov}}[1]$$

where σ_τ represents the standard error of τ. A smaller σ_τ indicates a more precise measurement.

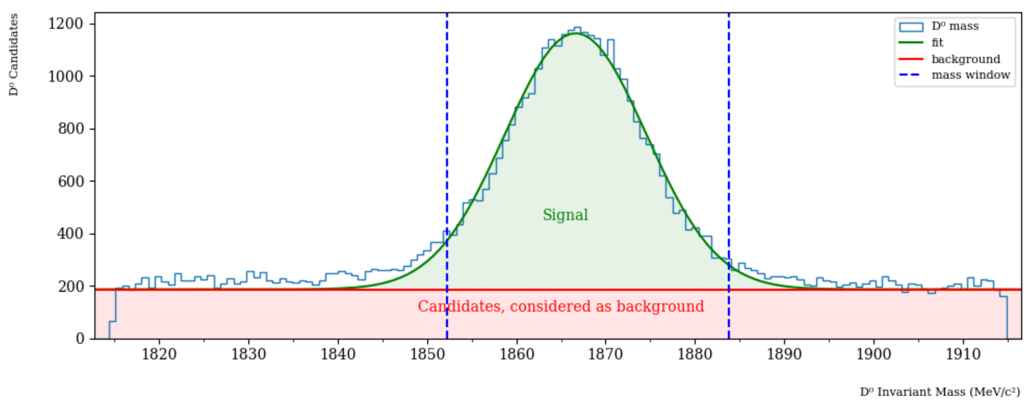


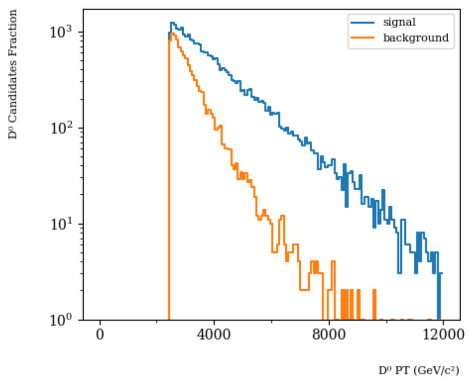
Figure 1: Mass Distribution

Plot 1 - Mass Distribution: Created with `np.histogram` from all candidate events, overlaid with the fitted Gaussian + background curve. Vertical dashed lines show the signal window; shaded bands denote sidebands.

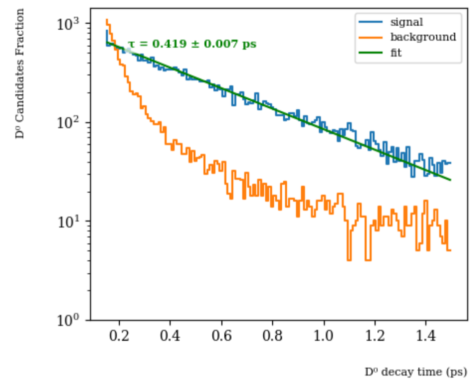
Plot 2 - PT Distribution: Generated from signal-window events after subtracting scaled sideband counts. Both background and subtracted signal PT spectra are plotted for comparison.

Plot 3 - Decay Time Distribution: Built from the same subtraction method; binned to balance statistical stability and fit precision. The exponential fit curve is drawn over the histogram and annotated with the fitted $\tau \pm \sigma_\tau$.

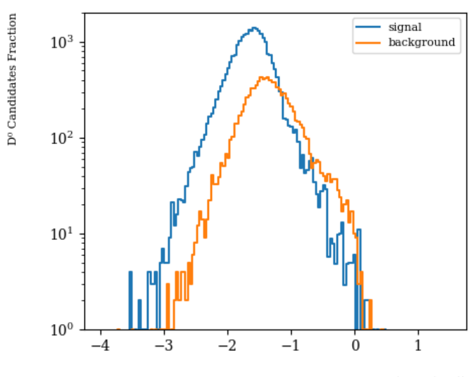
Plot 4 - logIP Distribution: Constructed after background subtraction, showing how candidates are distributed in vertex displacement space. The plot is updated dynamically when users change logIP cut settings via sliders.



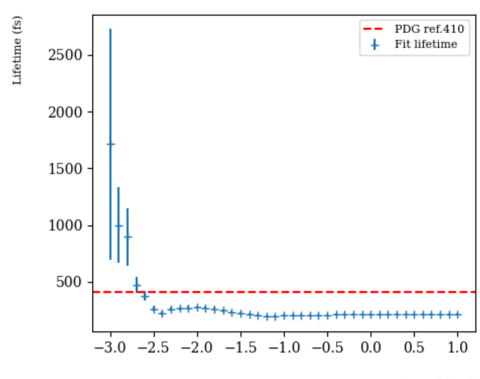
(a) PT Distribution



(b) Decay Time Distribution



(c) LogIP Distribution



(d) LogIP Cut vs Lifetime:

In the upgraded version of the exercise, an extra plot has been included to help students explore how their selection choices influence the measured lifetime.

Plot 5 - logIP Cut vs Lifetime: Here, the signal selection is iteratively re-run for a set of maximum logIP cut values. For each cut, the background subtraction and exponential lifetime fit are repeated, and the fitted τ value with its uncertainty is recorded. These results are plotted as discrete points with error bars versus the logIP cut threshold. The horizontal dashed line corresponds to the world-average D^0 lifetime from the Particle Data Group, allowing visual assessment of how the fitted lifetime converges or fluctuates as the cut changes. At low cuts, we keep almost all events, but the background can distort the lifetime measurement. As we increase the cut, we reject more background, so the lifetime becomes closer to the expected value. If the cut is too high, we start losing too much signal, and the lifetime measurement becomes less precise.

3.2 Before and after

The web application is now more interactive and engaging for students, featuring an introduction page that clearly explains the analysis steps. This modern design enhances the learning experience by providing easy access to the exercise and encouraging exploration of the data. Figures 3 and 4 show a visual comparison of the exercise interface before and after the recent upgrade for the main page.

Figure 3: Main page before

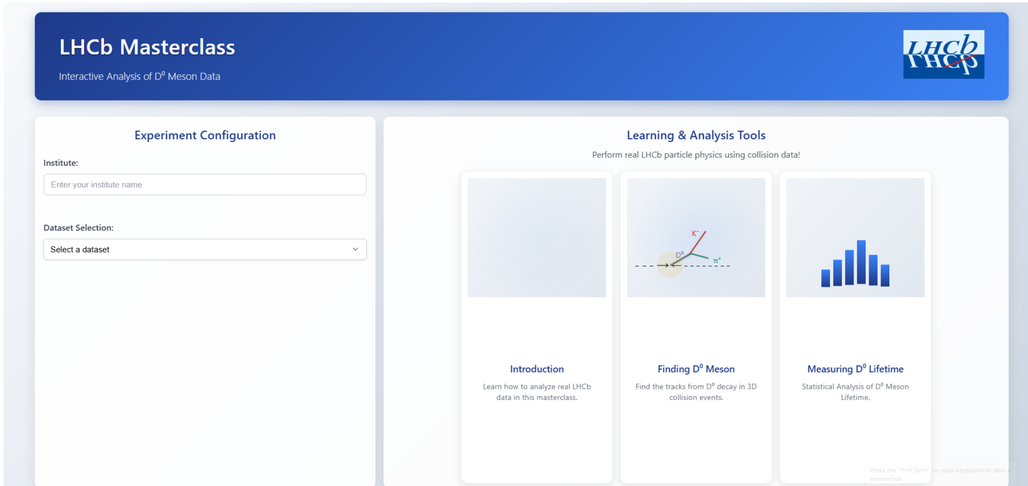


Figure 4: Main page after

Figures 5 and 6 present the respective changes before and after the recent upgrade for Exercise 2: Measuring the D^0 lifetime.

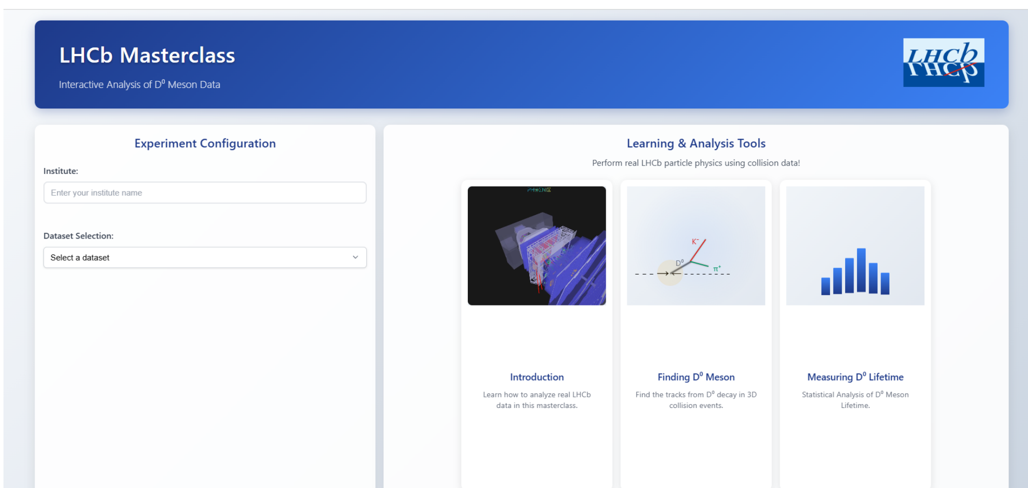


Figure 5: Exercise II before

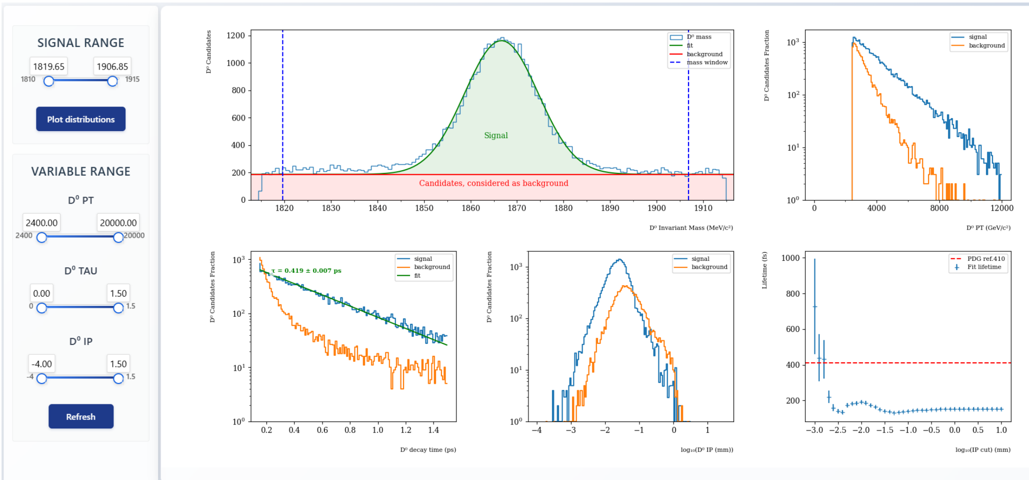


Figure 6: Exercise II after

Figures 7–13, shown in the Introduction section, illustrate the main concepts and setup of the exercise.

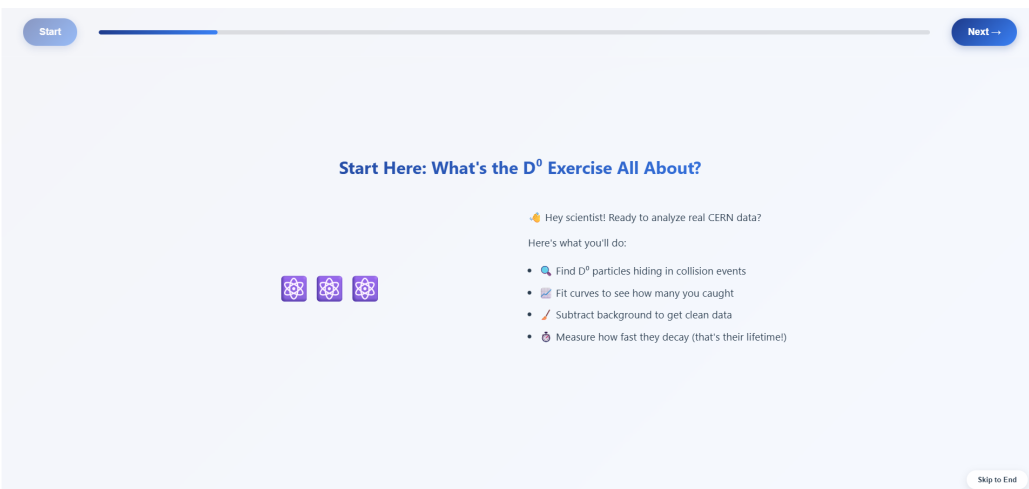


Figure 7: Overview of the Introduction section

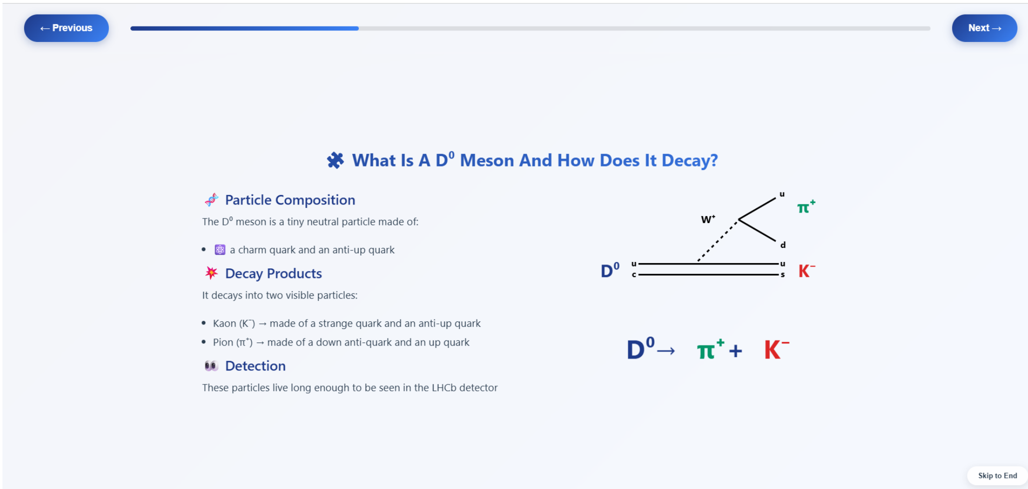


Figure 8: Overview of the Introduction section

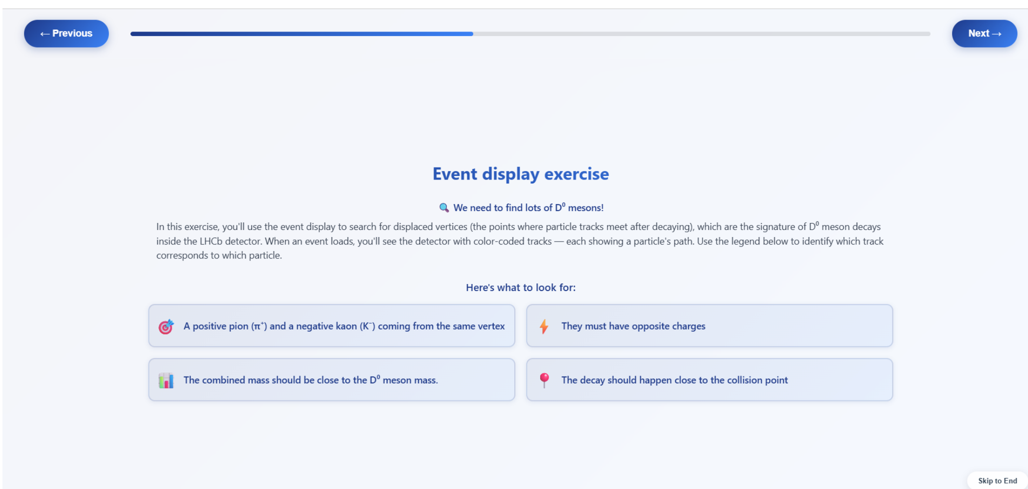


Figure 9: Overview of the Introduction section

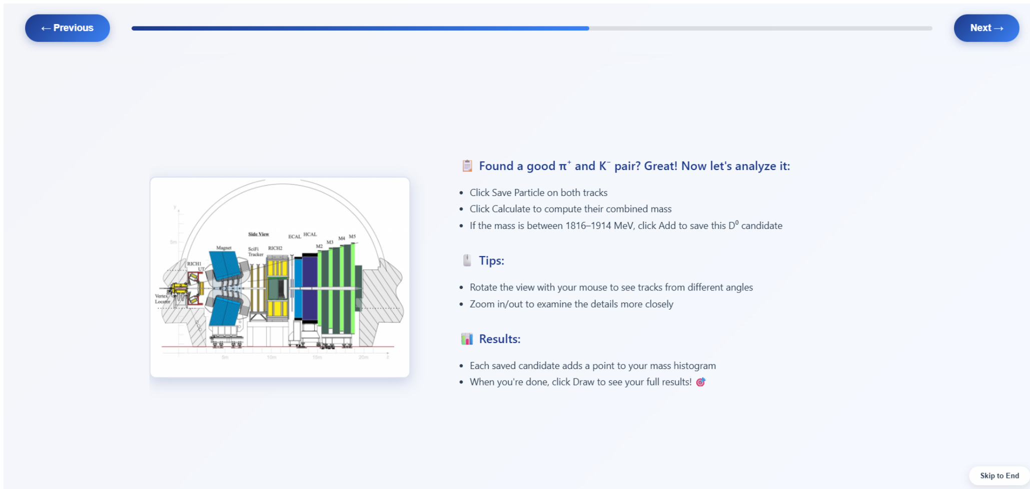


Figure 10: Overview of the Introduction section

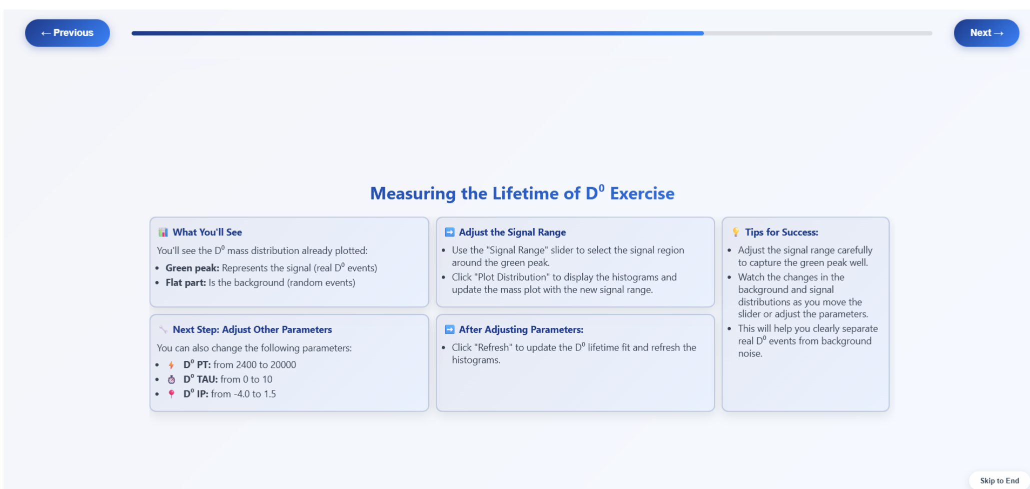


Figure 11: Overview of the Introduction section

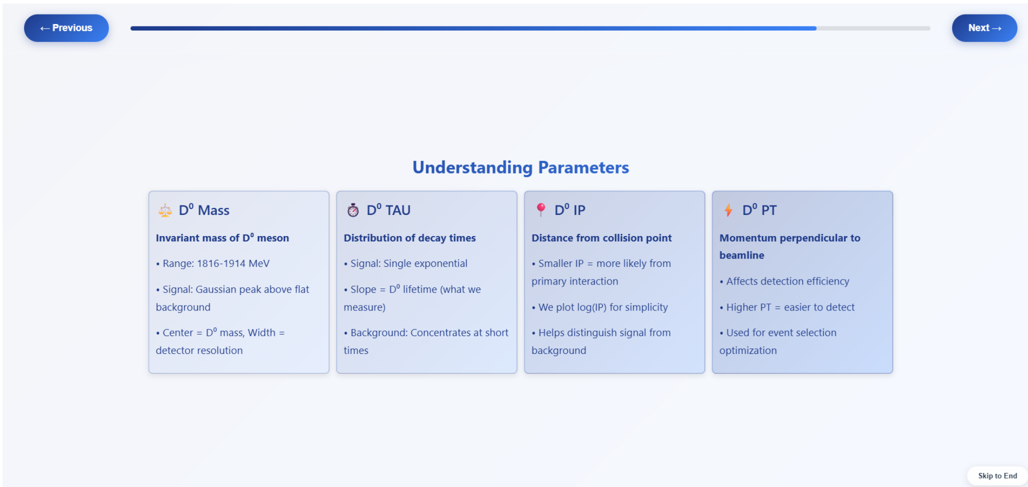


Figure 12: Overview of the Introduction section

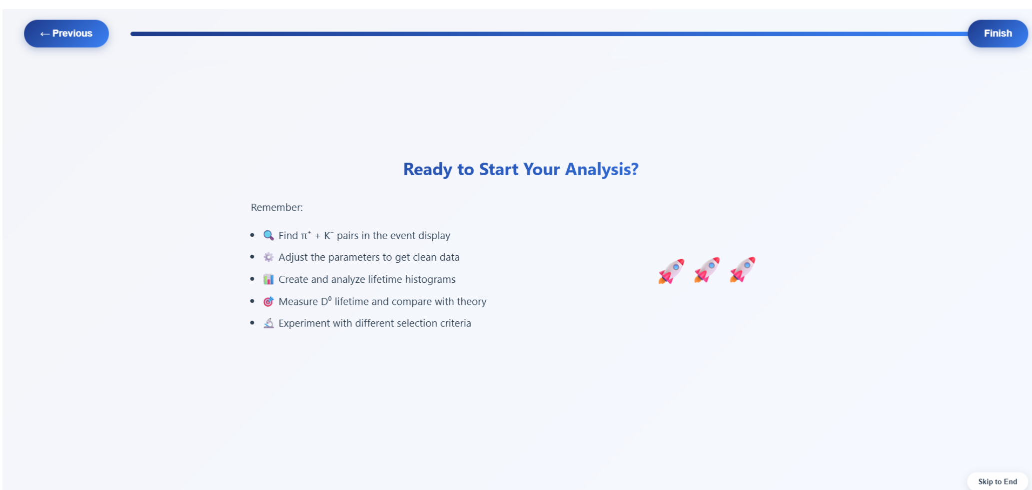


Figure 13: Overview of the Introduction section

4 Conclusion

The upgrade of the LHCb Masterclass D^0 lifetime measurement exercise has transformed an old tool into a modern, browser-based web application using updated 2024 LHCb collision data. It gives students an immersive experience in exploring D^0 meson decays through an intuitive event display, advanced filtering, and precise lifetime fitting. The new Python/PyScript interface with HSF Phoenix makes the exercise more interactive, visually engaging, and closer to real particle physics analysis.

Code Repository

The full source code for the upgraded application is available at GitLab: https://gitlab.cern.ch/arberish/lhcbmasterclass2025

References

[1] LHCb Masterclass Exercise: Measuring the D^0 Lifetime, https://lhcb-outreach.web.cern.ch/lhcbinternationalmasterclasses/d0-lifetime/, accessed 18 August 2025.

[2] CERN, The Large Hadron Collider (LHC), https://home.cern/science/accelerators/large-hadron-collider, accessed 18 August 2025.

[3] Official website of LHCb experiment at CERN, https://lhcb-public.web.cern.ch/, accessed 18 August 2025.

[4] International Particle Physics Outreach Group (IPPOG), International Masterclasses Hands on Particle Physics, https://ippog.org/, accessed 18 August 2025.

[5] Anaconda, Inc., PyScript, https://pyscript.net/, accessed 19 August 2025.

[6] Scikit-learn documentation, https://scikit-learn.org/stable/, accessed 19 August 2025.

[7] A. Trišović, *Measuring the D^0 Lifetime at the LHCb Masterclass*, in *Nuclear and Particle Physics Proceedings*, vol. 273–275, pp. 1215–1220, 2016. Presented at the 37th International Conference on High Energy Physics (ICHEP 2014), Valencia, Spain.

[8] Particle Data Group, D^0 Lifetime, https://pdglive.lbl.gov/Viewer.action?view=particle&pid=D0, accessed 19 August 2025.