Measuring γ with Time Dependent CP Violation in $B^0 \to D^{\mp}\pi^{\pm}$

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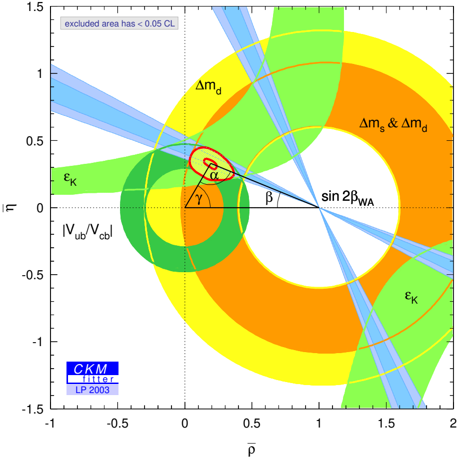
The CKM Triangle

- Standard model quark mass and flavour eigenstate mixing is described by the Cabibbo-Kobayashi-Maskawa (CKM) matrix.
- The CKM matrix can be used to construct unitarity triangles.
- The most well known CKM triangle is the 'B_d' triangle.
- Measuring the closure of these triangles is a precision test of the standard model.



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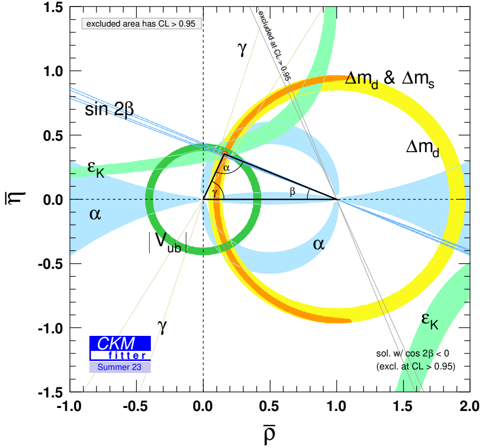
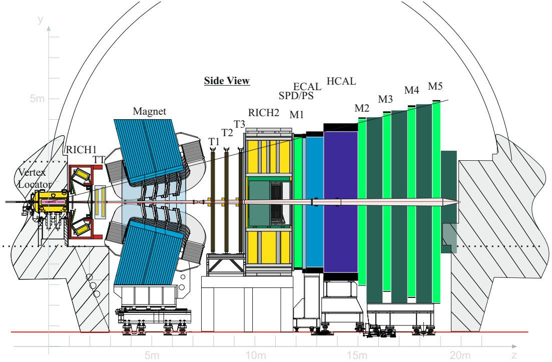


The LHCb Experiment



- The properties of the 'B_d' triangle can be accessed through measurements of B_d^0 mesons.
- These mesons are produced in abundance in *pp* collisions at the LHC.
- One of the many aims of the LHCb experiment is to study these mesons.

This analysis considers the $6\,\text{fb}^{-1}$ of data collected between 2015 and 2018 at the LHCb experiment.

Introduction to $B^0 \to D^{\mp}\pi^{\pm}$

- One of the possible decay channels of a B^0 meson is to a $D^{\mp}$ and a $\pi^{\pm}$.
- This decay can proceed through two paths: directly or through mixing.
- The differences in decay rate for initial B^0 meson flavour states to a given final state can be used to measure γ.

Previous results

Using the data collected by LHCb between 2008 and 2012 this channel was able to place bounds $\gamma \in [5, 86]^{\circ} \cup [185, 266]^{\circ}$.

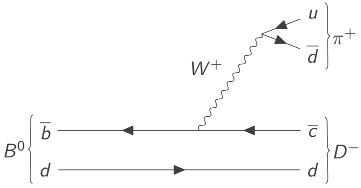


Figure: Direct decay of a B^0 meson to $D^- \pi^+$

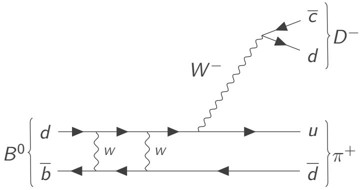


Figure: Decay of a B^0 meson to $D^- \pi^+$ via mixing to a $\overline{B}^0$ state.

Maths!

The decay rate for a given initial B^0 flavour to a final state is given by the following equations

$$\Gamma_{B^0 \to D^- \pi^+}(t) = \frac{1}{4\tau} e^{-t/\tau} \left[1 + C_f \cos(\Delta m\, t) - S_f \sin(\Delta m\, t)\right] \quad (1)$$

$$\Gamma_{B^0 \to D^+ \pi^-}(t) = \frac{1}{4\tau} e^{-t/\tau} \left[1 + C_{\bar{f}} \cos(\Delta m\, t) - S_{\bar{f}} \sin(\Delta m\, t)\right] \quad (2)$$

$$\Gamma_{\overline{B}^0 \to D^- \pi^+}(t) = \frac{1}{4\tau} e^{-t/\tau} \left[1 - C_f \cos(\Delta m\, t) + S_f \sin(\Delta m\, t)\right] \quad (3)$$

$$\Gamma_{\overline{B}^0 \to D^+ \pi^-}(t) = \frac{1}{4\tau} e^{-t/\tau} \left[1 - C_{\bar{f}} \cos(\Delta m\, t) + S_{\bar{f}} \sin(\Delta m\, t)\right] \quad (4)$$

$$C_f = -C_{\bar{f}} = \frac{1 - r_{D\pi}^2}{1 + r_{D\pi}^2} = 1 \quad (5)$$

$$S_f = -\frac{2 r_{D\pi} \sin\left[\delta - (2\beta + \gamma)\right]}{1 + r_{D\pi}^2} \quad (6)$$

$$S_{\bar{f}} = \frac{2 r_{D\pi} \sin\left[\delta + (2\beta + \gamma)\right]}{1 + r_{D\pi}^2} \quad (7)$$

How The Analysis Works

- Event selection
- Mass fits for signal extraction
- Time resolution
- Time dependent selection efficiencies
- Flavour tagging
- Decay time fit
- Systematic uncertainties

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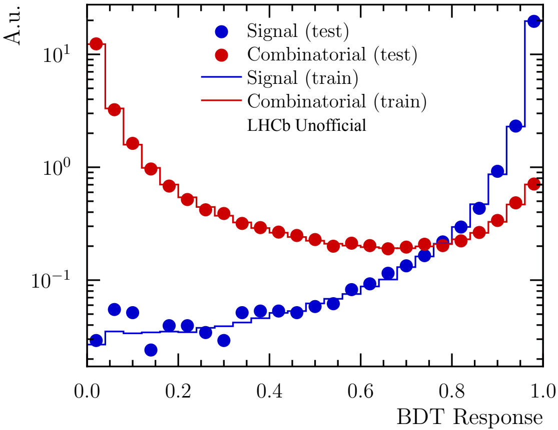
Event Selection

Combinatorial background is reduced through a BDT trained to identify these kinds of events.



Events are selected to reduce contamination from various background decays.

- Misidentified backgrounds:
  - $B^0 \to D^{\mp} K^{\pm}$
  - $B_s^0 \to D_s^{\mp} \pi^{\pm}$
  - $\Lambda_b^0 \to \Lambda_c^{\mp} \pi^{\pm}$
- Partially reconstructed backgrounds:
  - $B^0 \to D^{*\mp} \pi^{\pm}$
  - $B^0 \to D^{\mp} \rho^{\pm}$
- Combinatorial background.

Mass Fits

Fits to Simulated Data

To perform the final statistical separation of our signal from the background we use the *sPlot* method.

- Allows us to obtain per-event '*sWeights*'
- Requires a fit of our B^0 invariant mass data.

The first step to fitting our data is to perform fits to monte carlo simulation samples (MC).

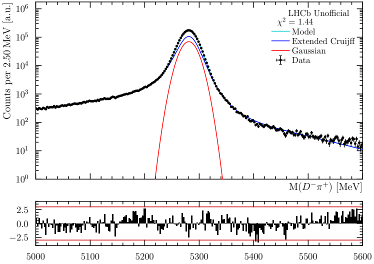


Figure: A fit to $B^0 \to D^{\mp}\pi^{\pm}$ MC data. The decay is fit to an extended cruijff + a gaussian.

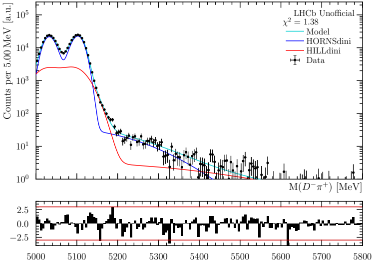
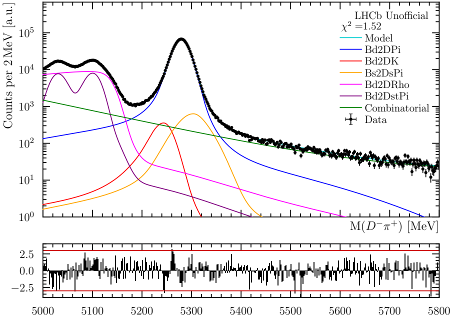


Figure: A fit to $B^0 \to D^{*\mp}\pi^{\pm}$ MC data. The decay is fit to a double HORNSdini distribution.

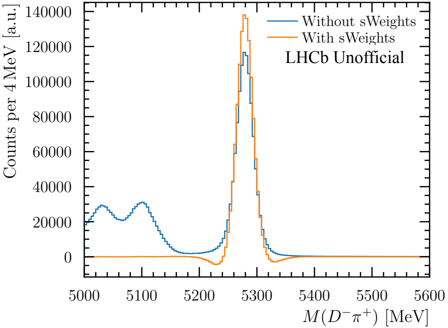
Mass Fits

Fit to Real Data

Using the individual fits to MC, we can fit the full data set. From this fit we are able to extract the *sWeights*.



$\longrightarrow$



Time Resolution

- Measured using prompt $D^{\pm}$ meson candidates in events with only 1 primary vertex.
- Candidate selection using *sPlot*, mass fit as a double crystal ball + a Gaussian.
- Sample P_T is reweighted to match the signal MC.
- Decay time is fit in 20 bins of decay time error.
- Decay time error is calibrated to resolution using a second order polynomial.
- Overall we obtain an **average time resolution of 47.6±0.3 fs**.

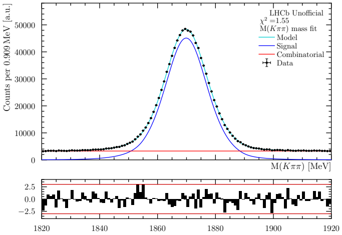


Figure: Mass fit of prompt $D^{\pm}$ mesons.

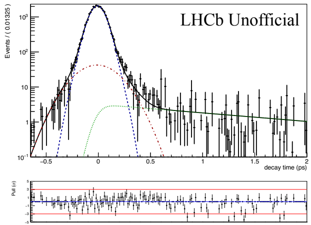


Figure: Decay time fit of prompt $D^{\pm}$ mesons with decay time error 59.35 fs $< \Delta\tau <$ 62.68 fs.

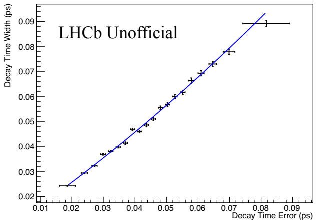
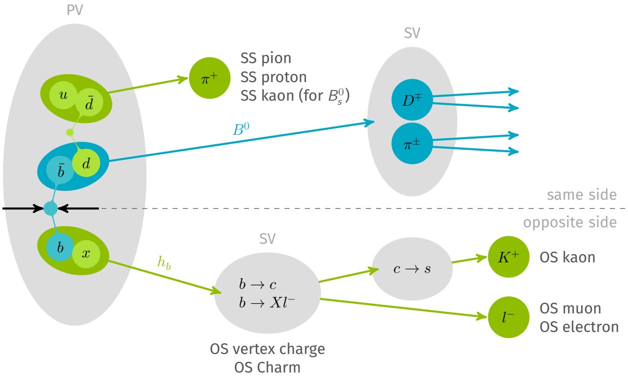


Figure: Measured time resolution vs decay time error.



In order to use equations 1-4, we must know the flavour of the B^0 meson at time of production.

- Three main varieties of algorithms: Opposite Side (OS), Same Side (SS) and Inclusive.
  - OS taggers: from other b quark in the initially produced pair.
  - SS tagger: from products of the b quark hadronization.
  - The inclusive tagger: all recorded tracks.
- Tagging algorithms output both a decision and a mistag probability.

Flavour Tagging

Algorithm Performance

- Flavour tagging performance is measured with the **effective tagging power**.

$$\varepsilon_{\text{eff}} = \varepsilon\left(1 - 2\omega\right)^2$$

  - Efficiency of the tagger, ε.
  - Average mistag probability, ω.
- Conventional taggers provide an effective tagging power of roughly **6%**.
  - This is consistent with observed performance in run 1.
- The Inclusive tagger provides a slight increase to nearly **7%**.

CP Fit

The final step is to fit the lifetime of the B^0 candidates using:

- Equations 1-4.
- *sWeights* from the mass fit.
- Time resolution, $\mathcal{R}(t - t')$.
- Time-dependent acceptance, $a(t)$.
- Flavour tagging decisions, d and mistag, η.
- External inputs for β, Δm, and $r_{D\pi}$

Which allows us to extract S_f, and therefore γ

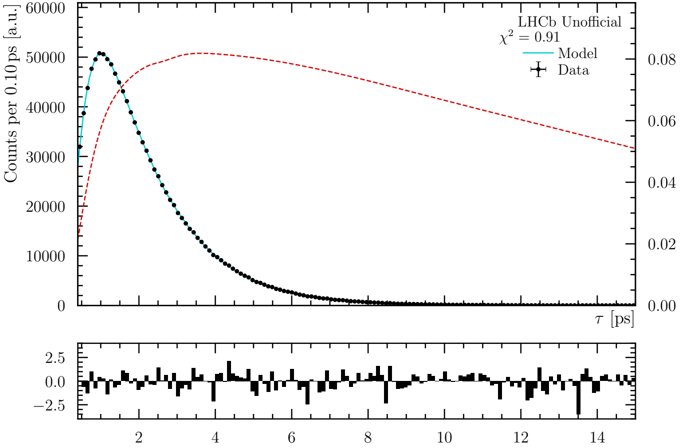


Figure: Time dependent selection efficiencies in MC data. Modelled as a cubic spline (in red)

Conclusion

- Much of the analysis is completed.
  - Combination of selection, BDT and *sPlot* allow for excellent signal extraction.
  - Flavour tagging algorithms are performing within expectations.
  - Time resolution is slightly improved over run 1.
- Still to do:
  - SS flavour tagging studies.
  - Final fit to lifetimes.
  - Systematic uncertainty.

BACK UP SLIDES

Full tagging results

Tagger	ε	ω	$\varepsilon\langle D^2\rangle = \varepsilon\,(1-2\omega)^2$
OS μ	$(9.685 \pm 0.030)\%$	$(29.636 \pm 0.024(\text{stat}) \pm 0.218(\text{cal}))\%$	$(1.607 \pm 0.006(\text{stat}) \pm 0.034(\text{cal}))\%$
OS e	$(3.858 \pm 0.020)\%$	$(32.506 \pm 0.030(\text{stat}) \pm 0.356(\text{cal}))\%$	$(0.472 \pm 0.003(\text{stat}) \pm 0.019(\text{cal}))\%$
OS K	$(19.681 \pm 0.041)\%$	$(37.142 \pm 0.013(\text{stat}) \pm 0.160(\text{cal}))\%$	$(1.302 \pm 0.004(\text{stat}) \pm 0.032(\text{cal}))\%$
Vertex Charge	$(20.461 \pm 0.042)\%$	$(36.045 \pm 0.013(\text{stat}) \pm 0.158(\text{cal}))\%$	$(1.594 \pm 0.004(\text{stat}) \pm 0.036(\text{cal}))\%$
OS c	$(5.313 \pm 0.023)\%$	$(34.635 \pm 0.019(\text{stat}) \pm 0.309(\text{cal}))\%$	$(0.502 \pm 0.003(\text{stat}) \pm 0.020(\text{cal}))\%$
SS π	$(83.576 \pm 0.038)\%$	$(43.063 \pm 0.007(\text{stat}) \pm 0.077(\text{cal}))\%$	$(1.609 \pm 0.003(\text{stat}) \pm 0.036(\text{cal}))\%$
SS p	$(41.623 \pm 0.051)\%$	$(43.942 \pm 0.010(\text{stat}) \pm 0.110(\text{cal}))\%$	$(0.611 \pm 0.002(\text{stat}) \pm 0.022(\text{cal}))\%$
OS Combination	$(39.530 \pm 0.050)\%$	$(34.261 \pm 0.014(\text{stat}) \pm 0.108(\text{cal}))\%$	$(3.917 \pm 0.009(\text{stat}) \pm 0.054(\text{cal}))\%$
SS Combination	$(88.207 \pm 0.033)\%$	$(42.207 \pm 0.007(\text{stat}) \pm 0.075(\text{cal}))\%$	$(2.143 \pm 0.004(\text{stat}) \pm 0.041(\text{cal}))\%$
OS + SS Combination	$(91.439 \pm 0.029)\%$	$(37.845 \pm 0.010(\text{stat}) \pm 0.070(\text{cal}))\%$	$(5.888 \pm 0.001(\text{stat}) \pm 0.065(\text{cal}))\%$
Inclusive	$(99.995 \pm 0.001)\%$	$(37.002 \pm 0.010(\text{stat}) \pm 0.066(\text{cal}))\%$	$(6.758 \pm 0.011(\text{stat}) \pm 0.069(\text{cal}))\%$

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