Study of angular distributions in $\tau$ production and decay at LHCb

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Abstract

Reconstruction of semi-leptonic $B$ meson decays with $\tau$ lepton at LHCb is very challenging, since more than one neutrino are present in the final state. A particular decay mode $B^0(B^0) \rightarrow D^{*\pm} \tau^\pm \nu_\tau(\bar{\nu}_\tau)$ with $\tau^\pm \rightarrow \pi^\pm \pi^\mp \pi^0(\pi^0)$ is most promising, since there are only two neutrinos in the final state, and both $B$ and $\tau$ decay vertices can be reconstructed. In this report, we will study the angular distributions of $\tau$ in the $B$ semi-leptonic decays and $\nu_\tau$ from the following $\tau$ decays, to see whether they can be used to distinguish the decay from the combinatorial background. All the work will be done using the simulated data. The comparison between theoretical expectations and Monte-Carlo generated events will be shown to be coherent, then the evolution of the distributions in simulation data through the different steps of the reconstruction process will be studied. Finally, the comparison between simulation data for signal and for background will reveal some angular domains or peaks that can be considered as background.
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Comparison between each of the four sign solutions for $\cos \theta_\tau$, calculated using MC-truth quantities, with the generated value of $\cos \theta_\tau$, for the selected events. Figure (a), (c), (e) and (g) give the distribution of the difference of each solution with the generated solution. Figure (b), (d), (f) and (h) show each solution versus the generated solution. For Figure (a), (b), (c), (d), we keep only the events with positive $\delta$ calculated with MC-truth quantities, positive $\delta^+$ calculated using MC-truth quantities, and for which the $+$ solution for $|\vec{p}_\tau|$ gives a physical $B$; For Figure (e), (f), (g), (h), we keep only the events with positive $\delta$ calculated with MC-truth quantities, positive $\delta^-$ calculated using MC-truth quantities, and for which the $-$ solution for $|\vec{p}_\tau|$ gives a physical $B$.

Angular distributions for the selected candidates, the other way of sorting the solutions. (a) shows the two solutions of $\cos \theta_\nu$ calculated with the two signs of equation 13 using the MC-truth quantities; (b) shows each sign solutions for $\cos \theta_\tau$, derived from MC-truth quantities.

Cosine of angle $\alpha$ between the 3 pions and the $\tau$ in lab-frame for the selected events: reconstructed versus generated. For a perfect reconstruction, we should only get events on the diagonal.

Cosine of angle $\alpha$ between the 3 pions and the $\tau$ in lab-frame for the selected events: reconstructed versus generated, with $\tau$ flight distance longer than 8 mm.

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$\cos \theta_\nu$ distribution calculated using the reconstructed quantities for the selected events.

Selective background angular distributions.

Extended background angular distributions.
1 Introduction

1.1 The LHCb experiment

1.1.1 Objectives

LHCb is one of the four detectors around the Large Hadron Collider (LHC), at CERN in Geneva. It has been designed to study the decay of $b$-hadrons created by the proton collisions in the accelerator. Its ultimate goal is to search for signs of physics beyond the Standard Model in rare phenomena such as CP violation.

1.1.2 The LHCb detector

The detector (Figure 1) is composed of a set of sub-systems to gather all the information required for studying the $B$-meson, in particular:

- The **Vertex Locator (VELO)**, composed of several silicon detectors in order to detect $B$-meson vertices,

- The **Ring Imaging Cherenkov (RICH)** detectors, that allow particle identification for charged particles, through the velocity measurement by the Cherenkov light cone emitted by a particle, and combined with the momentum information given by the tracking system,

- The **trackers**, composed of silicon detectors close to the beam axis (Inner tracker and Trigger tracker) and gas detectors further from the beam (Outer tracker), which detect the trajectory of charged particles,

- The magnets, which curve the trajectory of the charged particles, to allow momentum measurement with the tracking system,

- The **electromagnetic calorimeter**, that stops light particles (photons, electrons, positrons) by producing electromagnetic showers, to measure the particle energy,

- The **hadronic calorimeter**, that stops hadronic particles (protons, neutrons, pions, ...) by producing hadronic showers, to measure the particle energy,

- Muon chambers, composed of multi-wire proportional chambers for muon detection.

The LHCb detector is also composed of a **trigger**, to make a primary selection of the incoming events and reduce the number of events to an acceptable number for storage. The three-level trigger selects the most interesting events for the $B$-physics.
1.2 Software

The LHCb experiment requires a specific software environment, for both simulation and analysis. This environment is composed of several programs:

**GAUSS: Monte-Carlo simulation**  GAUSS[1] is a Monte-Carlo simulation program which simulates the whole experiment; it is special for LHCb configuration, and gives an electronic signal comparable to raw data. GAUSS performs two tasks:

- The generation of the particles produced in the proton collisions and their decay, using both **PYTHIA**[2] for the partons and hadronisation effects simulation, and **EvtGen**[3] for the simulation of the particles “history” (life-times, etc.), EvtGen includes detailed models for CP-violation and other crucial effects for the \( B \)-physics.
- The simulation of the detector response, i.e. the tracking of the particles. For this we use **GEANT**[4], which simulates the interactions of the particles with the different parts of the LHCb detector, and **BOOLE**[5] that simulates the digitalization of the signal. The trigger is simulated by **MOORE**[6].

In this study we used simulation data generated with the 2010 configuration (beam energy, etc.).

**BRUNEL: Reconstruction**  BRUNEL[7] performs the reconstruction on either simulation or real data. It gives DST files in output. In it we have the information about tracks, vertices, particle ID, and long-life particles (\( \pi^\pm, K^\pm, \gamma, p^\pm, e^\pm, \mu^\pm, \ldots \)). The DST files were the starting material
of this study. After this primary reconstruction, a “stripping” (additional selection) can be used to reduce the number of candidates.

**DaVinci: Analysis**  The DaVinci[8] framework, composed of a large collection of C++ libraries, allows the analysis of the data contained in the .dst files. For the needs of this study, several DVAlgorithms (C++ algorithms using DaVinci framework) were written to analyse and derive the data needed, from the information given in output of Brunel. At this stage one can apply cuts and selections to keep only the candidates of interest. In this study, the version v28r0 was used.

**ROOT: Data storing and analysis**  The information computed and collected in the DaVinci algorithms can be stored in ROOT files[10], in the form of “nTuples” (tabulars where all the variables are stored for each candidate). ROOT is a C++ interpretor developed at CERN, and allows powerful treatment of the final data without compilation (graphical representations, fits, additional computations, etc.)

![Figure 2: A schematic view of the software environment at LHCb [9]](image)

1.3  **Tau production and decay in semi-leptonic $B$ decays at LHCb**

The goal of this work is to study the angular distributions expected in $\tau$ production and decay in the semi-leptonic $B$-decay:

$$B^0(\bar{B}^0) \rightarrow D^{*\pm} \tau^\pm \nu_\tau(\bar{\nu}_\tau)$$  \hspace{1cm} (1)

which occurs with a branching ratio of $(1.6 \pm 0.5)\%$ [11], i.e. the highest branching ratio for a $B^0$ decay involving a $\tau$, and

$$\begin{cases} D^{*\pm} \rightarrow \bar{D}^0(D^0) \pi^\mp \ (67.7 \pm 0.5)\% \ [11] \text{ (most frequent } D^{*\pm} \text{ decay)} \\ \bar{D}^0(D^0) \rightarrow K^\pm \pi^\mp \ (3.89 \pm 0.05)\% \ [11] \end{cases}$$  \hspace{1cm} (2)

We will then study its decay through the mode:

$$\tau^\pm \rightarrow \pi^\pm \pi^\mp \bar{\nu}_\tau(\nu_\tau)$$  \hspace{1cm} (3)
which happens at \((9.32 \pm 0.07)\%\) [11]. The three pion tracks make this mode an easy one to reconstruct, because it defines a decay vertex, it has the highest branching ratio for \(\tau\) hadronic decays and moreover it involves only one neutrino. The whole topology of the decay is presented in Figure 3. The pion emitted in \(D^*\) decay is called a “slow pion” \((\pi_S)\) because of its low momentum.

In this study we will consider that the protons center of mass frame coincides with the detector frame. We will call the \(p-p\) center of mass the lab-frame.

1.3.1 Semi-leptonic \(B\) decay

The \(\tau\) direction angle in the semi-leptonic decay of the neutral \(B\) meson of mode 1 is represented in Figure 4. We call \(\theta_\tau\) the angle of emission of the \(\tau\) in the \(W\) rest-frame, with respect to the \(W\) direction in the lab-frame.

We get, for the angle \(\theta_\tau\), the following distribution [12]:

\[
\frac{d\Gamma(\cos \theta_\tau)}{d(\cos \theta_\tau)} \propto 2 + \alpha \sin^2 \theta_\tau + \frac{4}{3} A_{FB}(3 + \alpha) \cdot \cos \theta_\tau
\]  (4)
where we neglect the $\tau$ mass, which is a priori not appropriate, since the $\tau$ is a very massive lepton, but we will see later that it is not such a bad model. The Standard Model predicts that in the decay mode 1, the $c$-quark will be emitted preferentially with negative helicity\cite{12}. By the helicity conservation, and since $\nu_\tau$ (resp. $\bar{\nu}_\tau$) is always left-handed (resp. right-handed), we have a forward-backward asymmetry term in the distribution of $\theta_\tau$ helicity, defined as:

$$A_{FB} = \frac{\int_{-1}^{0} d\Gamma(\cos \theta_\tau) - \int_{0}^{1} d\Gamma(\cos \theta_\tau)}{\int_{-1}^{1} d\Gamma(\cos \theta_\tau)}$$ \hspace{1cm} (5)$$

The measured value for $A_{FB}$ is $A_{FB} = 0.1439 \pm 0.0043$\cite{11}. $\alpha$ describes the $D^*$ polarization. It can be known by studying $\theta_{D^0}$ distribution where we have no asymmetry term\cite{12}:

$$\frac{d\Gamma(\cos \theta_{D^0})}{d(\cos \theta_{D^0})} \propto 1 + \alpha \cos^2 \theta_{D^0}$$ \hspace{1cm} (6)$$

\subsection{Hadronic $\tau$ decay}

We also study the $\tau$-lepton decaying in a neutrino and three charged pions. In a first approximation, we will assume that in most cases, the three pions come from a resonance, and that the most frequent one is $a_1$ ($J = 1$). Thus, we consider the two-body hadronic decay:

$$\tau^\pm \rightarrow a_1^{\pm} \bar{\nu}_\tau (\nu_\tau)$$ \hspace{1cm} (7)$$

We look at the angle $\theta_\nu$ of emission of the neutrino in the $\tau$ rest-frame (Figure 5).

\begin{center}
Figure 5: Angle $\theta_\nu$ of emission of the neutrino from $\tau$ decay in the $\tau$ rest-frame ; $h$ is a hadron
\end{center}

Since $CP$ is conserved in the $\tau$ decays\cite{13}, the angular distribution involved in $\tau_R^+$ and $\tau_L^-$ will be the same. The theoretical distribution for $\theta_\nu$ is given by [13]:

$$\frac{d\Gamma(\cos \theta_\nu)}{d(\cos \theta_\nu)} \propto 1 + \alpha_h P_{h_\nu_\tau} \cos \theta_\nu$$ \hspace{1cm} (8)$$

with $h$ being any hadron: $h = \pi^\pm, \rho^\pm, a_1^{\pm}$. $h_\nu_\tau$ is the $\nu_\tau$ helicity in the $\tau$ rest-frame. The Standard Model predicts $h_{\nu_{\tau}} = -1$ and $h_{\bar{\nu}_{\tau}} = 1$. We have:

$$\alpha_h = \frac{m_{\tau}^2 - 2m_h^2}{m_{\tau}^2 + 2m_h^2}$$ \hspace{1cm} (9)$$
with \( h = \rho, a_1 \). So for \( h = a_1 \) (\( \rho^\pm \) does not decay into \( \pi^\pm \pi^\mp \pi^- \)), we get the theoretical value of \( \alpha \):

\[
\alpha_{\text{theo}} = \frac{m_{\tau}^2 - 2m_{a_1}^2}{m_{\tau}^2 + 2m_{a_1}^2} = 21.2 \cdot 10^{-3}
\]

(10)

\( P \) is the \( \tau \) polarization. We saw in section 1.3.1 that the \( \tau \) is emitted from the \( B \) with a non-zero polarization.
2 Acceptance studies

As a first step we would like to study whether generated angular distributions given in section 1 would be modified due to the detector acceptance and event selection cuts, that are unavoidable. Some considerations were then introduced:

- The LHCb angular acceptance, which is of 400 mrad in the forward direction,
- The efficiency of the detection and the reconstruction selection: only a fraction of the “incoming” particles will be detected and then pass the selection cuts applied for the reconstruction of the semi-leptonic $B$ decay of interest. We will call those events the “selected events” or candidates.

We would like to see how the distributions change, first with the only constraint of the LHCb angular acceptance, and then adding the constraint that the events must have been selected for the reconstruction. In this part, we will only consider the generated values of the angles, to study the acceptance effects.

2.1 Fitting of the theory with full acceptance simulation data

We studied the angular distributions for $4\pi$ angular acceptance with a Monte-Carlo sample of 10000 generated events of signal. We fit our generated angles with the theoretical formulae given in section 1. The angle distributions and the corresponding fit are given in Figure 6, and the parameters given by the two fits are summarized in Table 1.

The $\tau$ emission angle distribution given by equation 4 neglects the $\tau$ mass, and is therefore a bad model for our distribution. However, it still fits well the MC distribution, for $\alpha \approx 0.3$. We can also notice the linear angular distribution for $\cos \theta_\nu$, as expected from equation 8. The forward-backward asymmetry term is close to the theoretical value $A_{FB} = 0.144$.

2.2 Acceptance cuts

We then apply the selections explained above and study the changes that it introduces in the angular distributions. The parameters of the fit for each configuration are given in Table 1, and the fitted distributions for angles $\theta_\tau$ and $\theta_\nu$ are shown in Figure 6.

Approximated LHCb angular acceptance:

We used a second Monte-Carlo signal sample of 10000 events generated through LHCb angular acceptance, which is of 400 mrad. Fitted parameters remain unchanged comparing to the statistical errors.

Efficiency effects:

Using a larger sample of LHCb angular acceptance (100000 events), we studied the reconstruction efficiency effects, by looking only at the events that passed all the selection cuts for the reconstruction. The events must have been both detected and reconstructed. The detected events are selected by an algorithm PionCheck, that takes all 3-pions vertices and looks for corresponding generated pions. If they exist, the algorithm checks that the generated mother-particle of these 3 pions is a $\tau$. Then, the events have to pass all the selection cuts applied at the reconstruction. The statistics becomes smaller since the final reconstructed events are a very small fraction of the generated events.
(3400 over 100000). While the parameters for $\cos \theta_\tau$ distribution remain unchanged comparing to the statistical errors, the slope for $\cos \theta_\nu$ distribution increases. Therefore, efficiency correction is needed for the decay angle distribution of $\tau$ that has to be extracted from the LHCb data. However, this is beyond the scope of this study, and for everything that follows, we will only speak about the final selected candidates. The angular distributions that we will present have to be compared with distributions on Figures 6e and 6f.

<table>
<thead>
<tr>
<th>Fit function</th>
<th>$\cos \theta_\tau$</th>
<th>$\cos \theta_\nu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameters</td>
<td>$\alpha = 0.266 \pm 0.079$</td>
<td>slope = $(-6.49 \pm 1.77) \cdot 10^{-2}$</td>
</tr>
<tr>
<td>$A_{FB}$</td>
<td>$0.145 \pm 0.009$</td>
<td></td>
</tr>
<tr>
<td>Reduced $\chi^2$</td>
<td>1.22</td>
<td>1.06</td>
</tr>
</tbody>
</table>

| Parameters   | $\alpha = 0.173 \pm 0.075$ | slope = $(-4.21 \pm 1.76) \cdot 10^{-2}$ |
| $A_{FB}$     | $0.139 \pm 0.009$ | |
| Reduced $\chi^2$ | 0.61 | 1.03 |

| Parameters   | $\alpha = 0.359 \pm 0.143$ | slope = $(-16.7 \pm 2.97) \cdot 10^{-2}$ |
| $A_{FB}$     | $0.144 \pm 0.014$ | |
| Reduced $\chi^2$ | 2.24 | 1.51 |

Table 1: Parameters of the fits for the two angles and evolution through the acceptance effects
Figure 6: Angular distributions for the generated values of $\cos \theta_\tau$ ((a), (c), (e)) fitted with equation 4, and $\cos \theta_\nu$ ((b), (d), (f)) fitted with equation 8. The distributions for both angles are presented: (a) and (b): for full acceptance data (c) and (d): for LHCb angular acceptance data (e) and (f): for the candidates that passed the reconstruction
3 Computation of the angles

3.1 Reconstruction of MC-momenta from accessible data

With the help of a DaVinci algorithm that we called MCAlg, starting from the generated particles, their four-momenta and the position of the vertices:

- We boost the MC-neutrino emitted in the \( \tau \) decay in the \( \tau \) rest-frame,
- Then the \( \cos \theta_\nu \) is the scalar product of the neutrino momentum in the \( \tau \) frame with the \( \tau \) direction unit-vector in the lab frame
- We boost the \( \tau \) 4-momentum in the \( W \) rest-frame and the \( W \) 4-momentum in the \( B \) rest-frame,
- Then the \( \cos \theta_\tau \) is the scalar product of the two.

We have two neutrinos in the decay, that is two particles on which we will miss all information, the LHCb detector being unable to detect them. Therefore, due to the quadratic form of our reconstruction equations (see sections 3.1.1 and 3.1.2), the reconstruction will not be unique. To reconstruct the information about the whole decay, we start from the basic information that we get from the detector. The algorithm MCAlg computes the 4-momenta of our particles using the MC-truth information on the charged particles (\( \pi \), \( K \)) and about the vertices.

All the daughter particles of \( D^* \) are detected by the LHCb detector. Therefore, the \( D^* \) 4-momentum is measured. We also know the 4-momenta of the three pions from the \( \tau \). The VELO and the tracker also give us the positions of the vertices: the primary vertex (PV) where the \( B \) is produced, the \( B \) decay vertex where \( \tau \) is emitted (which is identical to the \( D^* \) vertex, defined by the \( D^0 \) and slow \( \pi \) intersection), and the \( 3\pi \) vertex (which is identical to the \( \tau \) decay vertex).

So the information that we know is:

- the \( D^* \) 4-momentum vector: \( P_{D^*} \)
- the 4-momentum vectors of each pion coming from the \( \tau \): \( P_{\pi_1}, P_{\pi_2} \) and \( P_{\pi_3} \)
- the direction of the \( \tau \), \( \vec{p}_\tau/|\vec{p}_\tau| \), from the \( \tau \) production and decay vertex positions
- the direction of the \( B \), \( \vec{p}_B/|\vec{p}_B| \), from the \( B \) production and decay vertex positions
- the masses of the particles: \( M_B, M_\tau, M_\nu = 0 \)

3.1.1 Reconstruction of \( P_\tau \) and \( \theta_\nu \)

From a kinematic point-of-view, we can consider the \( \tau \) decay as the two-body decay:

\[
\tau \longrightarrow (3\pi) \nu \tag{11}
\]

Let \( \hat{u}_\tau \) be the unit vector for the \( \tau \) direction. We have the following system of equations:

\[
\begin{align*}
\vec{p}_\tau &= \vec{p}_{3\pi} + \vec{p}_\nu \\
E_\tau &= E_{3\pi} + E_\nu \\
E_\nu^2 - |\vec{p}_\nu|^2 &= 0 \\
E_\tau^2 - |\vec{p}_\tau|^2 &= M_\tau^2 \\
\vec{p}_\tau/|\vec{p}_\tau| &= \hat{u}_\tau
\end{align*}
\tag{12}
\]
This gives us two solution for $|\vec{p}_\tau|$: 

$$|\vec{p}_\tau| = \frac{(M^2_\tau + M^2_3) |\vec{p}_{3\pi}| \cos \alpha \pm E_3 \sqrt{(M^2_\tau - M^2_{3\pi})^2 - 4M^2_\tau |\vec{p}_{3\pi}|^2 \sin^2 \alpha}}{2(E^2_{3\pi} - |\vec{p}_{3\pi}|^2 \cos^2 \alpha)}$$  \hspace{1cm} (13)$$

with $\alpha$ the angle between $\vec{p}_\tau$ and $\vec{p}_{3\pi}$, in the $p - p$ center of mass system (which one must not mistake with the $\alpha$ parameter of equation 4).

In the $\tau$ rest-frame, the two solutions correspond to a $(3\pi)$ system emitted with symmetric angles with respect to the normal of $\tau$ direction (Figure 7).

![Figure 7: The two possible configurations for the $\tau$](image)

Both solutions are physical, but only one of them is the one that has been generated. Both solutions are relatively close to each other as shown on Figure 8. We consider the one which is closest to the MC-truth solution as the “correct” solution, and we will call the other solution the “wrong” solution. We calculate $\theta_\nu^{\text{correct}}$ (resp. $\theta_\nu^{\text{wrong}}$) using the “correct” (resp. “wrong”) $\tau$ 4-momentum. Figure 11a shows the distributions for $\cos \theta_\nu^{\text{correct}}$ and $\cos \theta_\nu^{\text{correct}}$ together with the MC-truth distribution. We can see that both solutions, calculated with the generated quantities, give an angular distribution which is very close to the MC-truth angular distribution. The difference between the “correct” solution and the generated one, gives an estimation of the rounding errors inherent to the code (Figure 10a).

However, we have to deal with some precision problem for $\cos \theta_\nu$ near zero, i.e. for the case where the neutrino is emitted perpendicularly with the $\tau$ in the $\tau$ rest-frame. It corresponds to the case $p_+ = p_-$ in equation 13.

We can see in the expression of $|\vec{p}_\tau|$ (equation 13) that in the expression under square root, that we call $\delta$:

$$\delta = (M^2_\tau - M^2_{3\pi})^2 - 4M^2_\tau |\vec{p}_{3\pi}|^2 \sin^2(\alpha)$$  \hspace{1cm} (14)$$

enters a difference between very large numbers to the power 4, and this difference is always close to zero. $\delta$ is thus extremely sensitive to the precision on the quantities ($3\pi$-momentum, angle $\alpha$). $\delta$
happens to be often negative due to these precision problems. Figure 9 shows the distribution of $\delta$ for selected events, where $\delta$ is calculated using the MC-truth values. The negative $\delta$ values indicate the precision problem. In all the following studies, we will only take into account the candidates for which $\delta > 0$. On every figure that will follow, we will only show the distributions for the events with positive $\delta$.

![Figure 8: “Wrong” solution vs. “correct” solution for $|\vec{p}_\tau|$ in MeV](image)

**Figure 8:** “Wrong” solution vs. “correct” solution for $|\vec{p}_\tau|$ in MeV

![Figure 9: $\delta$ of equation 14, calculated with the MC-truth quantities for the selected events. A non-negligible part of events have $\delta < 0$ due to precision problems.](image)

**Figure 9:** $\delta$ of equation 14, calculated with the MC-truth quantities for the selected events. A non-negligible part of events have $\delta < 0$ due to precision problems.

### 3.1.2 Reconstruction of $P_B$ and $\theta_\tau$

The $B$ decay can be seen the same way than the $\tau$ decay: we consider the two-body decay:

$$B \longrightarrow (D^* \tau) \, \nu$$  \hspace{1cm} (15)
with $P_{(D^+\tau)}^{\text{correct, wrong}} = P_{D^+} + P_{\tau}^{\text{correct, wrong}}$. Similarly we get:
\[
|\vec{p}_B| = \frac{(M^2_{D^+\tau} + M^2_B)|\vec{p}_{D^+\tau}| \cos \alpha' \pm E_{D^+\tau} \sqrt{(M^2_B - M^2_{D^+\tau})^2 - 4M^2_B|\vec{p}_{D^+\tau}|^2 \sin^2 \alpha'}}{2(E^2_{D^+\tau} - |\vec{p}_{D^+\tau}|^2 \cos^2 \alpha')}
\]
with $\alpha'$ being the angle between $\vec{p}_B$ and $\vec{p}_{D^+\tau}$ in the lab frame.

Each one of the two solutions for $p_\tau$ will give two solutions for $p_B$. We will therefore obtain four solutions. However, for some events among the generated events, the “wrong” solution for $|\vec{p}_\tau|$ (the one that was not generated) can lead to a non-physical solution for $P_B$, associated with $P_{D^+}$, i.e. the mass of the system ($D^+\tau_{\text{wrong}}$) can in some cases be higher than $M_B$. In this case, we only get two solutions for $p_B$. Still, for the majority of the candidates we have four solutions.

The same precision problem arises with $\delta'$:
\[
\delta' = (M^2_B - M^2_{D^+\tau})^2 - 4M^2_B|\vec{p}_{D^+\tau}|^2 \sin^2 \alpha'
\]
Again, we systematically reject the negative values of $\delta'^+$ when calculating “+” quantities (see Table 2), and the negative values of $\delta'^-$ when calculating “-” quantities.

We have an estimation of the code rounding errors on the reconstruction of $|\vec{p}_B|$ by comparing the generated one and the “correct” one calculated using MC-truth quantities (Figure 10b).

**Figure 10:** Rounding errors: “correct” recalculated versus MC-truth solution, for (a) $|\vec{p}_\tau|$ (MeV), (b) $|\vec{p}_B|$ (MeV)

### 3.2 Choosing between the solutions

As far as we deal with simulation data, we know that the right solution for $p_B$, i.e. the closest one to $p^M_B$, comes from the “correct” solution of $p_\tau$. We will consider the right solution as the one which is closest to the MC-truth solution, among the two solutions given by the correct $\tau$.

We recalculate our $\theta_\tau$ angle, and observe the angular distribution given by each of the four solutions (Figure 11b). The distributions differ significantly from each other. Therefore, we need to be precise
when choosing the right solution for $p_\tau$, despite the fact that the distributions given by the two solution for $p_\tau$ are relatively close to each other.

<table>
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<th>Derived from</th>
<th>Quantities</th>
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<tr>
<td>$p_\tau^{\text{correct}}$ (closest to $p_{\tau}^{MC}$)</td>
<td>$P_B^{\text{correct}}$ (closest to $p_{B}^{MC}$)</td>
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<tr>
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Table 2: The two different ways of sorting the data

Unfortunately, it appears that it is very hard to choose between the “right” and “wrong” solutions without the MC-truth information, and it will be possible only for some events. Since the results have to be comparable to real data, another point of view is adopted. Since we cannot know the distributions of the “correct” and “wrong” quantities, we will sort them using the sign that was used in the reconstruction of the momenta they derive from. Table 2 shows the two ways that can be adopted to sort the data.

As we see on Figure 11, it would be though primordial, if we wanted to estimate the parameters of the distribution in equations 4 and 8, to know the “correct” quantities. There are several solutions to this problem, though none of them will allow complete knowledge of the “correct” quantities. The best one is to keep only one sign ($++$, $+-$, $-+$, or $--$, see Table 2) and treat the solutions deriving from this sign as the “correct” ones. On Figure 12, we show the generated $\cos \theta_\tau$ versus the $\cos \theta_\tau$ of each sign calculated using MC-truth. One can see that taking the $+-$ solution as correct would minimize the error. In fact, we can see that the most symmetric (and therefore less biased) difference between calculated and generated values are obtained for opposite signs ($\pm$ solution for $\tau$ with $\mp$ solution for $B$); but the width of the distribution is minimal in the case of the $+-$ solution. We choose to study the angular distributions of the four different solutions, regardless to what are the generated ones. This way, the MC distributions will be directly comparable to real data and will be treated as the true signal signature. Figure 13 shows the two angle distributions, for each signs, using MC-truth quantities on the selected events. We can see that $\cos \theta_\nu^+ = -\cos \theta_\nu^-$, by construction, and that $+$ solution corresponds to forward emission of $\nu_\tau$ in the $\tau$ rest-frame, whereas $\cos \theta_\nu^+$ corresponds to backward emission of $\nu_\tau$ in $\tau$ frame. For all the angular distributions that will follow, the graphs will present:

- $\cos \theta_\nu^+$, $\cos \theta_\nu^-$, $\cos \theta_\nu^{\text{generated}}$ for events with $\delta > 0$;
- $\cos \theta_\nu^{+,+-}$ for events with $\delta > 0$ and $\delta^+ > 0$, when the $+$ solution for $\tau$ is physical;
- $\cos \theta_\nu^{-+}$ for events with $\delta > 0$ and $\delta^- > 0$, when the $-$ solution for $\tau$ is physical;
or:

- \( \cos \theta^\text{correct}_\nu, \cos \theta^\text{wrong}_\nu, \cos \theta^\text{generated}_\nu \) for events with \( \delta > 0 \);
- \( \cos \theta^\text{correct-correct,correct-wrong}_\tau \) for events with \( \delta > 0 \) and \( \delta^\text{correct} > 0 \);
- \( \cos \theta^\text{wrong-correct,wrong-wrong}_\tau \) for events with \( \delta > 0 \) and \( \delta^\text{wrong} > 0 \), when the wrong solution for \( \tau \) is physical;
Figure 11: Distribution of $\cos \theta_\nu$ and $\cos \theta_\tau$, recalculated with the MC-truth information on the pions, kaons, and vertices. We give the solution of $\theta_\nu$ calculated using the “correct” solution for $\tau$-momentum of equation 13 (i.e., closest to generated $\tau$ momentum), and the solution calculated using the “wrong solution”; we also show the generated $\cos \theta_\nu$. $\cos \theta_\tau$ is given for “correct-correct”, “correct-wrong”, “wrong-correct” and “wrong-wrong” solutions (see Table 2). The gap at zero in $\cos \theta_\nu$ distribution is due to the $\delta$ precision problem at $\cos \theta_\nu \sim 0$ (see paragraph 3.1.1).
Figure 12: Comparison between each of the four sign solutions for $\cos \theta_\tau$, calculated using MC-truth quantities, with the generated value of $\cos \theta_\tau$, for the selected events. Figure (a), (c), (e) and (g) give the distribution of the difference of each solution with the generated solution. Figure (b), (d), (f) and (h) show each solution versus the generated solution.

For Figure (a), (b), (c), (d), we keep only the events with positive $\delta$ calculated with MC-truth quantities, positive $\delta'$ calculated using MC-truth quantities, and for which the + solution for $|\vec{p}_\tau|$ gives a physical $B$;

For Figure (e), (f), (g), (h), we keep only the events with positive $\delta$ calculated with MC-truth quantities, positive $\delta'$ calculated using MC-truth quantities, and for which the − solution for $|\vec{p}_\tau|$ gives a physical $B$. 
Figure 13: Angular distributions for the selected candidates, the other way of sorting the solutions. (a) shows the two solutions of $\cos \theta_\nu$ calculated with the two signs of equation 13 using the MC-truth quantities; (b) shows each sign solutions for $\cos \theta_\tau$, derived from MC-truth quantities.
4 Reconstruction of the decay

So far we have only studied the generated quantities. Now we introduce the reconstruction effects, that is, we recalculate all our quantities, and our angles $\theta_\nu$ and $\theta_\tau$, using the reconstructed quantities for the initial pions, kaons, vertices. To calculate the reconstructed quantities we wrote a second algorithm $\text{RDA}lg$. This one is only applicable to the events that were reconstructed, and effectuates the same calculations as $\text{MC}alg$ but starting from the reconstructed information about the pions, kaons, and vertex positions.

4.1 Reconstruction of $\tau$ momentum and $\theta_\nu$

The same calculation than in section 3.1 is done, with equation 13, starting from:

- reconstructed 3 pions momentum,
- reconstructed $\alpha$ angle between $\tau$ and $3\pi$ directions in the lab

With a perfect reconstruction, these quantities would be very close to the corresponding generated quantities. However, there is always some error at the reconstruction, due to the precision of the detection and to the interpretation that has to be made at the reconstruction. To have an idea about the reconstruction error on the $3\pi$ momentum, Figure 14a shows the distribution of the generated momentum for the $3\pi$ in the lab for the selected events, $|p_{3\pi}|$, and Figure 14b shows the difference between the generated and reconstructed $|p_{3\pi}|$. The error is of the order of the percent, which shows a very good reconstruction for $|p_{3\pi}|$. We also show the generated distribution for $\alpha$ and the difference between generated and reconstructed $\alpha$ (Figures 15a and 15b). The difference is of the order of 50%.

![Figure 14](image-url)
Figure 15

Figure 16 gives cos α generated versus cos α reconstructed. The generated and reconstructed α do not show any correlation between them; we see that the reconstructed cos α is very preferentially higher than the generated one. In other words the reconstruction makes the 3π momentum artificially parallel to the τ direction.

Figure 16: Cosine of angle α between the 3 pions and the τ in lab-frame for the selected events: reconstructed versus generated. For a perfect reconstruction, we should only get events on the diagonal

cos α is computed with the 3π momentum vector and with the τ direction vector. To understand this error about the cos α reconstruction, we show in Figure 17 the angle between the generated and reconstructed directions, for the τ and for the 3π. The 3π direction is very well reconstructed, but we have a large error on the τ direction, which is calculated using the τ production and decay vertices positions. Figure 18a shows the absolute distance in mm between the generated and reconstructed vertices, for the D* vertex (which is identical to the B decay vertex where τ is produced), and for the 3π vertex (which is the τ decay vertex). We see that there is less uncertainty about the 3π vertex than about the D* vertex. This is due to the fact that the slow pion and the D^0 are emitted
almost parallel, due to their low velocity in the $D^*$ rest-frame; thus, the curved slow pion track gives an imprecise vertex point combined with the straight $D^0$ direction. Figure 18b gives the generated $\tau$ flight distance. It is relatively small compared to the error about the vertices positions shown on Figure 18a; this explains the large error about the $\tau$ direction reconstruction. As a matter of fact, applying cuts on the $\tau$ flight distance reveals slightly better correlation between $\cos \alpha$ generated and reconstructed. Figure 19 shows $\cos \alpha$, reconstructed versus generated, with the $\tau$ flight distance above 8 mm.

(a) Angle between generated and reconstructed $3\pi$ momentum vector (rad)

(b) Angle between generated and reconstructed $\tau$ direction vector (rad)

Figure 17

(a) Absolute distance between generated and reconstructed vertex position, for $D^*$ and $3\pi$ vertices (mm)

(b) $\tau$ generated flight distance in the lab (mm)

Figure 18
Figure 19: Cosine of angle $\alpha$ between the 3 pions and the $\tau$ in lab-frame for the selected events: reconstructed versus generated, with $\tau$ flight distance longer than 8 mm

Due to these imprecision sources at the reconstruction, the $\delta$ of equation 14 calculated using the reconstructed quantities becomes negative for more events than the $\delta$ derived from MC-truth quantities (Figure 20). As a final information about the reconstruction error on the $\tau$, we show the relative difference:

$$\frac{\Delta p_\tau}{p_\tau} = \frac{|\vec{p}_\tau|_{\text{MC-truth}} - |\vec{p}_\tau|_{\text{reconstructed}}}{|\vec{p}_\tau|_{\text{MC-truth}}}$$

(18)

between $\tau$ momentum (+ or −), calculated from MC-truth and from reconstructed quantities, on Figure 21. The error is of the order of 30%.

The distribution of $\cos \theta_\nu$ derived from reconstructed quantities is given in Figure 22. It is very peaked at $\cos \theta_\nu \sim \pm 1$. Like we saw, the reconstruction makes the angle $\alpha$ very small. Once boosted in the $\tau$ rest-frame, $\alpha$ becomes $\pi - \theta_\nu$. We see on Figure 23 that small $\alpha$ angles in lab frame correspond to small $\theta_\nu$ angles in the $\tau$ frame.

Figure 20: $\delta$ of equation 14 derived from the reconstructed quantities

Figure 21: Relative difference $\frac{\Delta p_\tau}{p_\tau}$ between the $\tau$ momenta derived from MC-truth and from reconstructed quantities, for solutions + and −
Figure 22: $\cos \theta_\nu$ distribution calculated using the reconstructed quantities for the selected events.

Figure 23: Difference of generated and reconstructed $\cos \alpha$ (angle of $3\pi$ with $\tau$ in the lab frame), versus the difference of generated and reconstructed angles $\cos \theta_\nu^+$ in the $\tau$ rest-frame. $\alpha$ boosted in $\tau$-frame becomes $\pi - \theta_\nu$. We can see that small angles $\theta_\nu$ in $\tau$ frame correspond to small angles $\alpha$ in lab frame.

In order to verify that the big differences that we observe between $\cos \theta_\nu$ computed with generated and reconstructed quantities are due to the errors about the $\tau$ direction reconstruction, we computed $\cos \theta_\nu$ using all reconstructed quantities except for the $\tau$ direction for which we took the generated value. Figure 24 shows the difference of $\cos \theta_\nu$ computed with generated and reconstructed quantities, in the case where the reconstruction used all reconstructed quantities and in the case where the reconstruction used all reconstructed quantities but generated $\tau$ direction vector. We see that the difference becomes very peaked at zero; the bad $\tau$ direction vector reconstruction...
is therefore the reason of the poor $\cos \theta_\nu$ reconstruction.

(a) Difference between $\cos \theta_\nu$ calculated using MC-truth quantities and $\cos \theta_\nu$ calculated using reconstructed quantities

(b) Difference between $\cos \theta_\nu$ calculated using MC-truth quantities and $\cos \theta_\nu$ calculated using reconstructed quantities except for the $\tau$ direction for which the generated value was used

Figure 24

4.2 Reconstruction of $B$ momentum and $\theta_\tau$

The same analysis can be done for the $B$ reconstruction. Here we will only give the main additional sources of error that appear in the $B$ reconstruction. If we look for example at the angle between the generated and the reconstructed $B$ direction in the lab, on Figure 25a, we see that we have a peak at $\pi$. That is, some $B$ are emitted backward (and, thus, decay before having been created). These are non-physical $B$; it is due to precision problems about the vertex positions. $B$ is emitted from the primary vertex (PV). Figure 25b shows the absolute distance between generated and reconstructed primary vertex positions, and we see that the PV is very well reconstructed. Therefore, again the problem comes from the bad $D^*$ vertex reconstruction. We decided to apply cuts on the $B$ direction.
such that we keep only the forward-emitted \( B \) (and thus, with a physical lifetime). The distribution of \( \cos \theta_r \) derived from reconstructed quantities is presented in Figure 26.

Figure 25

Figure 26: \( \cos \theta_r \) distribution calculated using the reconstructed quantities for the selected events
5 Comparison between signal and background

Although the signal distributions already give some information, it would help to have other criteria to distinguish between signal and background, since the signal distributions are rather flat. To add some information, we studied the same distributions in different background cases. Some sources of background that one could get about the reconstruction of this decay are:

- Wrong-sign background: a $D^{*-}$ and $\tau^-$ (or $D^{*+}$ and $\tau^+$) are reconstructed as coming from a non-physical $B^{-\pm}$ or $B^{\pm\pm}$

- Error on the $D^0$: wrong $K^{-}\pi$ combinations

Any error in combining the information given by the detector leads to adding some background. So far we looked at the MC-truth and reconstructed information demanding a match between generated and reconstructed particles; this way we had no background sources in our selection. For the background angular distributions analysis, we studied a sample of Monte-Carlo $B \rightarrow D^{*}\pi\pi\pi$ events. The generated decay is:

\[ B^0 \rightarrow D^{*-} a_1^+ \rightarrow D^{*-} (\rho^0\pi^+) \rightarrow D^{*-} (\pi^+\pi^-\pi^+) \]  \hspace{1cm} (19)

and reversed signs. In this work, we observed two types of background:

1. The mother particle of a pion coming from $a_1$ or from $\rho^0$ has been reconstructed as a $\tau$ (we will call it “selective background”),

2. The mother particle of any pion found in the decay has been reconstructed as a $\tau$ (which we will call “extended” background).

5.1 Selective background

For the selective background, we proceeded in a similar way than in the case of the reconstructed signal. With the help of a new PionCheck algorithm, we verify that the three reconstructed pions do have a corresponding generated pion, and that this generated pion comes either from an $a_1$ that comes from a $B$, or from a $\rho^0$, that comes from an $a_1$ that comes itself from a $B$. In other words we ask for the three pions to come from the generated decay. Then we ask that these three pions have been reconstructed as coming from a $\tau$ coming from the decay $B \rightarrow D^{*}\tau\nu_{\tau}$. All the cuts applied to the candidates are exactly the same than in the case of the signal sample (same RDAlg algorithm). The angular distributions are presented in Figure 27.

With these cuts, we see that the number of selected candidates is very low, and so the statistics is worst than what we had for the signal. It is rather difficult to observe significant changes, still we see that $\cos \theta^+_{\nu}$ and $\cos \theta^-_{\nu}$ both cover the whole domain of angles.

The study of this special case of background gives information about the angular distributions when the $B$ hadronic decay of mode 19 has been reconstructed as the $B$ semi-leptonic decay of mode 1. However this is a very special case, we see that it gives very few candidates, and it does not take into account the largest part of background.

5.2 Extended background

To obtain larger statistics, and to extend the observation at a very large set of different background sources, we suppress the condition that the three pions must come from actual generated pions,
emitted by either $a_1$ or $\rho_0$. This time we take all the reconstructed pions that have been reconstructed as coming from a $\tau$ coming itself from $B$ through the decay of mode 1. These pions might come from anything, if their three tracks seem to converge, they will be very easily reconstructed as coming from $\tau$. This time, we get much better statistics: around 40000 times more candidates for extended background than for selective background, but we only took 1/26th of the data for extended background study presented in Figure 28.

We can observe, like in the case of selective background that the distribution of $\cos \theta_{\nu}$ is still symmetric with respect to zero ($\cos \theta^+_{\nu} = -\cos \theta^-_{\nu}$), by construction, and that there are no distinct domains for $+$ and $-$ solution. We can also notice on Figure 28b that there is a tendency of the backgroud to peak at $\cos \theta_{\tau} = -1$, which corresponds to a $\tau$ emitted parallel to $W$ and backward in the $W$ rest-frame. We saw in the study of the signal angles that on the contrary, forward and small angles $\theta_{\tau}$ are favoured.
(a) $\cos \theta_{\nu}$ distribution

(b) $\cos \theta_{\tau}$ distribution

Figure 27: Selective background angular distributions
Figure 28: Extended background angular distributions
6 Conclusion

In this work, we presented the study of angular distributions for the $\tau$ emission and decay in the channel

$$\begin{align*}
B^0(\bar{B}^0) & \rightarrow D^{*\pm} \tau^\pm \nu_\tau(\bar{\nu}_\tau) \\
D^{*\pm} & \rightarrow D^0(D^0) \pi^\mp \rightarrow K^\pm \pi^\mp \pi^\mp \\
\tau^\pm & \rightarrow \pi^\pm \pi^\mp \pi^\mp \pi^\mp \bar{\nu}_\tau(\nu_\tau)
\end{align*}$$

A linear distribution for the $\nu_\tau$ angle of emission in $\tau$-frame, and a quadratic behaviour for the angle of $\tau$ emission in the $W$ boson rest-frame are expected and generated in our simulation data. The effects of the geometrical acceptance of LHCb detector, the detection efficiency and the reconstruction selection on the angular distributions have been studied by taking these considerations into account successively. While the angular distribution of $\tau$ emission from the $B$ decay is not strongly affected, the angular distribution of the neutrino emission from the $\tau$ decays shows a noticeable distortion once the effect of the event reconstruction is taken into account.

We presented the reconstruction principle for the decay, starting from the observable information. The presence of two neutrinos in the decay imposes to deal with two solutions for the neutrino momentum, resulting in four solutions for the $B$ momentum. There is no absolute way to know which one of the four is the true one; yet one would still be more or less correct by choosing only the solutions that were derived from opposite signs for $|\vec{p}_\tau|$ and $|\vec{p}_B|$. An intrinsic precision problem about the calculation of $|\vec{p}_\tau|$ does unfortunately not allow accurate study of the case where $\nu_\tau$ is emitted with a large angle in the $\tau$ rest-frame.

In this work we presented the angular distributions in the case of each of the four possible solutions. We studied the angular distributions of the four solutions calculated using the generated and reconstructed information. Large differences are observed between generated and reconstructed angles. The main sources of errors are the reconstructed $D^*$ vertex which suffers from big uncertainty due to intrinsic kinematics of the decay.

Then we studied the same angles for two different types of background: one particular type of background, coming from the decay $B \rightarrow D^* a_1$, and a more general case of background where any 3 pions with converging tracks and that have been reconstructed as coming from a $\tau$ are considered.

The main differences with the signal angular distributions are:

- $+$ and $-$ solutions for $|\vec{p}_\tau|$ both give $\nu_\tau$ emitted either forward or backward in $\tau$-frame, whereas in the case of the signal, $+$ solution gives $\nu_\tau$ emitted forward and $-$ solution backward in the $\tau$ rest-frame. The backward neutrinos given by the $+$ solution as well as the forward neutrinos given by the $-$ solution are thus background without doubts.

- In the $W$ rest-frame, $\tau$ seems to be emitted preferentially backward and parallel to $W$ direction, whereas in the case of the signal, it is emitted preferentially forward with small angles with respect to the $W$ direction. The peaks at $\cos \theta_\tau \sim -1$ can therefore for a part be considered as background.

From these informations, we already have some tools to discriminate part of the background in the reconstruction of the semi-leptonic $B$-decays involving a $\tau$. However, to allow a more accurate study of the distributions, some improvements remain to be done. In particular we could:

- Use Monte-Carlo samples with higher numbers of initial generated events, to improve the statistics of our results;
• Improve the accuracy of the reconstruction by adding some further selection on the candidates, such as longer particles time of flight, or smaller difference between generated and reconstructed $D^*$ vertices.
References


[12] David BRITTON, Semileptonic decays of the B-meson, McGill University, Montréal (Canada), 1993
