EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

TRACK MATCHING FOR LHCB UPGRADE 2

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Abstract

This study is focused on the tracking performances of LHCb Upgrade 2, scheduled during the Long Shutdown 4 in 2030. This upgrade will enable the experiment to take data at a luminosity up to $1.5 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1}$ (almost 7.5 times higher than Upgrade1). In particular, this project concentrates on track matching: an algorithm finds tracks passing through the full LHCb detector by combining a track segment reconstructed in the detectors before the dipole magnet with another segment reconstructed after the magnet. A $\chi^2$ technique is used to discriminate the different possible combinations. Results are expressed in term of efficiency and ghost rate.
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Chapter 1

Introduction

The LHCb experiment is situated at one of the four experiment points around CERN’s Large Hadron Collider. It is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$, designed for the study of particles containing b or c quarks. Its main goal is to look for indirect evidence of new physics in CP violation and rare decays of beauty and charm hadrons.

The choice of the detector geometry is justified by the fact that at high energies both the b and b-bar hadrons are predominantly produced in the same forward or backward cone (approximately 10 mrad to 300 mrad). The layout of the LHCb spectrometer is shown in figure 1.1. The right-handed coordinate system adopted has the $z$ axis along the beam, and the $y$ axis along the vertical.

![Figure 1.1: Layout of the detectors inside LHCb experiment.](image-url)
1.1 LHCb Upgrade 2

The LHCb Upgrade I is currently under construction \cite{2} and will start data taking in 2021 after LHC Long Shutdown 2 (LS2). LHCb Upgrade II will be installed during LS4, with operations beginning in LHC Run 5 which is scheduled to start in 2031 (Fig.1.2). This Upgrade II experiment will operate at instantaneous luminosities of up to $1.5 \times 10^{34}$ cm$^{-2}$ s$^{-1}$, an order of magnitude above Upgrade I.

This study is focused on the information coming from the tracking detectors which are: before the magnet, VErtex LOcator (VELO) and Upstream Tracker (UT) and after the magnet the T-stations. \cite{4}

In Upgrade 2 for the UT, one of the ideas proposed by the LHCb Collaboration is to replace the Silicon strips of Upgrade 1 with pixels.

On the T-stations, it is proposed to construct hybrid technology modules incorporating scintillating fibres in the outer region and silicon pixels (or sensors) in the more central region (MT and IT), known as the Mighty Tracker (Fig.1.3). These detectors define the baseline used in this project.

Figure 1.2: Timeline of accelerator and experiment operations over the decade 2021 to 2031. The periods of operations of the LHC and HighLumi-LHC are indicated and the long shutdowns (LS). \cite{3}

Figure 1.3: Design of the Mighty Tracker which will be incorporated on the T-stations for Upgrade 2 run. It is composed of a silicon central region (Inner Tracker and Middle Tracker) and an outside part with Scintillating Fibers (SciFi). \cite{5}
1.2 Tracking

Charged particles trajectories are reconstructed through the different elements of the tracking system. It is important to note that no tracking element is located inside the dipole magnet, and therefore accurate momentum reconstruction will require the combination of segment seeds from both sides of the magnet. “Long” tracks (see Fig. 1.4) are here essential for the analysis: they are derived from particles hitting every tracking detector before and after the magnet (in this case Velo, UT and T-stations).

![Figure 1.4: Schematic representation of LHCb track types.](image)

This study’s objective is to evaluate the efficiency of Track Matching at Upgrade 2 Luminosity. Segments of tracks before the magnet (upstream) are matched with segments of tracks after the magnet by using extrapolation of the tracks in the magnetic field region (see Fig. 1.5). A $\chi^2$ is built for each of these combinations and the pair with minimum $\chi^2$ is chosen as final match. A sample of 20 simulated events which contained each a $B^0_s \rightarrow \phi\phi$ decay, at a luminosity of $1.5 \times 10^{34}$ cm$^{-2}$ s$^{-1}$ is analyzed.

![Figure 1.5: Track matching for LHCb: an upstream segment (before the magnet) has to be matched with another segment after the magnet.](image)
Chapter 2

Matching system: $\chi^2$ for each match

As explained in the previous chapter, a value of $\chi^2$ is calculated for each of the possible track combinations. Position information of each one of the tracking detectors is used, smeared considering the expected resolution for the Upgrade 2 detectors. These resolutions are employed for this study:

- 55 $\mu$m in x and y for the VELO
- 80 $\mu$m in x and y for the UT
- 80 microns in x and y for the T-stations

2.1 Position related term

Different approaches are considered to calculate the $\chi^2$ in the bending (xz) or non bending(yz) plane.

2.1.1 Bending plane term

In the xz plane, the track is curved by the magnetic field of the dipole. The technique used for this algorithm is called "kink" approximation: if the particle trajectory before the magnet is considered as a straight line, all the bending produced by the magnetic field can be approximated by a sharp "kink" at a specific z position, called $z_{mag}$.

This method is used to calculate the first term of the $\chi^2$. As showed in Fig. 2.1, the upstream segment is extended as a straight line by using the first hit on the Velo and last hit on the UT to evaluate the $x_{pre}$ at $z_{mag}$ position. The same procedure is applied but backwards for the T-stations by using first (T1) and last (T3) hit to calculate the $x_{meas}$. 
The first $\chi^2$ term is then evaluated in this way:

$$\chi^2_{bending} = \frac{(x_{\text{pre}} - x_{\text{meas}})^2}{\sigma_x^2}$$

The $\sigma$ here used is calculated by looking at the standard deviation of the "real" $x_{\text{pre}} - x_{\text{meas}}$ distribution which means of the true track combinations (Appendix A). In this way, the resolution of the approximation can be evaluated.

Figure 2.1: Bending plane $\chi^2$ calculation by using the "kink" approximation.

### 2.1.2 Non-bending plane term

In the yz plane, the particle trajectory is actually a straight line because there is no effect of the magnetic field (or very small). No approximation is then needed and $y_{\text{pre}}$ and $y_{\text{meas}}$ can be extrapolated in the same way as the previous section (see Fig. 2.2).

Figure 2.2: Non-bending plane $\chi^2$ calculation by extending both upstream and downstream segments to $z_{\text{mag}}$ position.
In this case, another term can be added to build the $\chi^2$:

$$\chi^2_{\text{nonbending}} = \frac{(y_{\text{pre}} - y_{\text{meas}})^2}{\sigma_y^2} + \frac{(t_{y\text{pre}} - t_{y\text{meas}})^2}{\sigma_{t_y}^2}$$

The second term added depends on the slopes of the segments as showed in Fig. 2.3. The first segment is still extended to the $z_{\text{mag}}$ value but then this point is used to evaluate the slope predicted with the first hit point on the T-stations. The measured slope is just calculated by using the first and last hit on the T-stations.

![Figure 2.3: Non-bending plane $\chi^2$ calculation by using the slopes of the upstream and downstream segments as main information.](image)

The final $\chi^2$ is:

$$\chi^2 = \frac{(x_{\text{pre}} - x_{\text{meas}})^2}{\sigma_x^2} + \frac{(y_{\text{pre}} - y_{\text{meas}})^2}{\sigma_y^2} + \frac{(t_{y\text{pre}} - t_{y\text{meas}})^2}{\sigma_{t_y}^2}$$

### 2.2 Momentum

An idea to improve the precision of this minimum $\chi^2$ technique is to add to its expression a term related to the momentum of the particle. This can be evaluated considering the bending of its trajectory.

By studying the difference in slope of the different tracks segments (Fig. 2.4), the momentum of the particle can be approximated. This could be done by considering the difference of slopes between Velo and T-stations ($p_{\text{meas}}$) or Velo-UT ($p_{\text{pred}}$).
Figure 2.4: Strategy to evaluate the momentum of the particle by using the slopes of the different segments on Velo, UT and T-stations.

Figure 2.5 shows four different plots of delta slope vs momentum of the particle divided into: top-bottom for positive and negative charge and left-right for Velo-UT and Velo-Tstat slopes. The distributions are then fitted with a $1/x$ type of function with 4 parameters: $z = \frac{a}{x} + d$. In fact the greater the delta slope is, the less the momentum of the particle should be. At this point, by knowing the Velo-UT and Velo-Tstat slope difference and by using these four functions just found, the predicted and measured momentum can be calculated.

A fourth term is then added to the $\chi^2$ obtaining:

$$\chi^2 = \frac{(x_{pre} - x_{meas})^2}{\sigma_x^2} + \frac{(y_{pre} - y_{meas})^2}{\sigma_y^2} + \frac{(t_{pre} - t_{meas})^2}{\sigma_{ty}^2} + \frac{(p_{pre} - p_{meas})^2}{\sigma_p^2}$$

The $\sigma_p$ is calculated in a similar way of the sigma previously introduced by considering the $p_{pre} - p_{meas}$ distributions but in this case for different momentum regions. By fitting these sigmas obtained as showed in Fig. 2.6, a momentum sigma dependent on $p_{meas}$ is achieved.
Figure 2.5: Delta slope plots on the particle momentum. These graphs are divided by top-bottom into charge +1 and -1 and left-right into Velo-UT and Velo-Tstations slopes. The distributions are fitted with a 1/x function type to predict the momentum of the particle by knowing the difference in slope.

Figure 2.6: This plot is showing how the momentum sigma is depending on $\rho_{\text{meas}}$ (momentum evaluated from the Velo-Tstat delta slope difference).
2.3 Timing

An idea for the LHCb Upgrade 2 is to add time information on the new tracking detectors. This section will then investigate how time data can be used to improve the track matching efficiency considering for example a 30 ps resolution achieved by new technologies.

A new term dependent on time could be added to the $\chi^2$:

$$\frac{(t_{\text{pre}} - t_{\text{meas}})^2}{\sigma_t^2}$$

where the $t_{\text{meas}}$ is considered as the time of the last hit on the T-stations (subtracting its matching Primary Vertex (PV) time) with a 30 ps resolution.

An idea to evaluate the $t_{\text{pre}}$ is presented on figure 2.7. The total path traveled by the particle is calculated into four parts:

- a straight line between the Primary Vertex and the first hit on the Velo
- an arc of circle using two hits on the Velo and one hit on the UT (a perpendicular line from the middle of both segments can be drawn and their intersection defines the radius of the circle)
- an arc of circle in the magnet by using the value of the magnetic field, the momentum and the mass of the particle analyzed
- an arc of circle by using three hits on the T-stations (first, last and a middle one)

Knowing the total path traveled, the momentum and the mass of the particle the expected time can be easily calculated.
Figure 2.7: Schematic view of the total path calculation for the particle trajectory. This can be divided into 4 parts: a straight line between the Primary Vertex and the first hit on the Velo, an arc of circle in Velo-UT, an arc of circle in the magnet by using the magnetic field and the mass of the particle and finally another arc of circle inside the T-stations.
Chapter 3

Performances and Results

3.1 Efficiency and Ghost Rate

To evaluate the performance of this algorithm technique, two parameters are used:

\[
\text{Efficiency} = \frac{\text{Correct Matches}}{\text{Total Long Tracks}}
\]

\[
\text{Ghost Rate} = \frac{\text{Wrong Matches}}{\text{Found Matches}}
\]

The errors on these quantities are calculated by using the formula: \( \sigma_{\epsilon} = \sqrt{\frac{\epsilon(1-\epsilon)}{N}} \).

The goal of the algorithm is of course to maximize the efficiency and minimize the ghost rate. This study focuses at first on improving to the maximum the efficiency. Then some techniques to reduce the ghost rate are presented.

3.2 Performance with baseline \( \chi^2 \)

This algorithm was applied first to a \( B_S \rightarrow \phi\phi \) MC sample with Luminosity \( 2.0 \times 10^{33} \, \text{cm}^{-2} \, \text{s}^{-1} \) using the Upgrade 1 detectors layout. This is very useful to have a first direct comparison with a MC sample of the same event type, but higher luminosity (\( 1.5 \times 10^{34} \, \text{cm}^{-2} \, \text{s}^{-1} \) currently considered baseline for Upgrade 2) using the upgraded layout. Table 3.1 shows the first results. Upgrade 2 results are really promising compared to the Upgrade 1 results considering the much higher density of tracks that the algorithm has to process. Table 3.2 shows how efficiency and ghost rate vary as we increase the momentum of the particles studied. The efficiency increases as the momentum increases because the straight line track model used better approximates the real particle’s trajectory.
### 3.3 Results with momentum

This focuses on the analysis of the addition of the momentum term to the \( \chi^2 \). Table 3.3 shows the results obtained by using the momentum term described in the previous chapter. The efficiency improves of about 1% compared to the three terms \( \chi^2 \) technique. The third result in the table displays the outcome using the expected momentum resolution. In this case we consider the following momentum term:

\[
\chi_{p_{\text{exp}}} = \frac{(p_{\text{VeloUT}} - p_{\text{Tstat}})^2}{\sigma_{p_{\text{VeloUT}}}^2 + \sigma_{p_{\text{Tstat}}}^2}
\]

A resolution \( \sigma_{p_{\text{VeloUT}}} \) of 15% is used to estimate \( p_{\text{VeloUT}} \) and a resolution \( \sigma_{p_{\text{Tstat}}} \) of 1% to estimate \( p_{\text{Tstat}} \).

| Starting \( \chi^2 \), Algorithm p approximation, Expected p resolution |
|-----------------------------|-----------------------------|-----------------------------|
| Efficiency                  | 0.932 ± 0.003               | 0.942 ± 0.003               | 0.966 ± 0.002               |
| Ghost Rate                  | 0.173 ± 0.004               | 0.160 ± 0.004               | 0.147 ± 0.004               |

Table 3.3: Efficiency and Ghost rate evaluated by adding a momentum term inside the \( \chi^2 \).

### 3.4 Results with timing

This section presents results obtained by adding a time term to the initial \( \chi^2 \). For the moment, the technique explained in the previous chapter is still under investigation. As a first approach, it is possible to employ the timing information by faking a smearing, for example 30 ps resolution which should be achieved by the new tracking detectors. Table 3.4 shows results by using a 30 or 1 ps resolution in both the upstream and downstream segments.
This "fake" time term is evaluated in this way:

\[ \chi_{t_{\text{exp}}} = \frac{(t_{\text{VeloUT}} - t_{\text{Tstat}})^2}{\sigma^2_{t_{\text{VeloUT}}} + \sigma^2_{t_{\text{Tstat}}}} \]

where \( \sigma_{t_{\text{VeloUT}}} \) and \( \sigma_{t_{\text{Tstat}}} \) are the resolutions that were here just discussed. For this study both \( t_{\text{VeloUT}} \) and \( t_{\text{Tstat}} \) are the Primary Vertex time of the segments (considering their original track) smeared by the selected resolutions.

<table>
<thead>
<tr>
<th></th>
<th>Starting ( \chi^2 )</th>
<th>Expected time resolution (30 ps)</th>
<th>Fake time resolution (1 ps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Efficiency</td>
<td>0.932 ± 0.003</td>
<td>0.944 ± 0.003</td>
<td>0.970 ± 0.002</td>
</tr>
<tr>
<td>Ghost Rate</td>
<td>0.173 ± 0.004</td>
<td>0.167 ± 0.004</td>
<td>0.144 ± 0.004</td>
</tr>
</tbody>
</table>

Table 3.4: Efficiency and Ghost rate evaluated by adding a time term inside the \( \chi^2 \).

### 3.5 Reducing the Ghost Rate

An idea to reduce the ghost rate is to reject matches which have very large \( \chi^2 \). This is mostly used to exclude the Velo-UT segments that do not reach the T-stations (not long tracks) and are of course wrongly matched with a segment after the magnet. This is increasing the number of fakes and by consequence the ghost rate.

By plotting all the \( \chi^2 \) from real matches, it is possible to pick a threshold cut at a certain percentage (see Fig. 3.1).

![Figure 3.1: The plot of the real match’s \( \chi^2 \) is showed. The thresholds are showed as percentages considering the value of the \( \chi^2 \).](image)
Table 3.5: Efficiency and ghost rate results for different threshold cuts using only the position $\chi^2$ technique.

<table>
<thead>
<tr>
<th>Threshold</th>
<th>NO</th>
<th>99%</th>
<th>98%</th>
<th>97%</th>
<th>96%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Efficiency</td>
<td>0.933 ± 0.003</td>
<td>0.933 ± 0.003</td>
<td>0.930 ± 0.003</td>
<td>0.924 ± 0.003</td>
<td>0.917 ± 0.003</td>
</tr>
<tr>
<td>Ghost Rate</td>
<td>0.171 ± 0.004</td>
<td>0.167 ± 0.004</td>
<td>0.161 ± 0.004</td>
<td>0.157 ± 0.004</td>
<td>0.151 ± 0.004</td>
</tr>
</tbody>
</table>

The results of efficiency and ghost rate by applying this rejection method are showed in Fig. 3.2 and in Table 3.5. As presented in the graph, by increasing the rejection of a few percentages (99-98-97 %) the ghost rate can be reduced of 1 % while keeping the efficiency almost constant.

Figure 3.2: Efficiency and Ghost rate are plotted in function of the percentage of $\chi^2$ threshold cut.
Conclusions

Due to the changes in luminosity and in the detector layouts for LHCb Upgrade2, it is necessary to revisit and improve the tracking algorithms. In particular, this study focuses on the potential to reconstruct long tracks (with hits on all the tracking subdetectors of LHCb) which are the most exploited track type for the experiment’s measurements.

The results are expressed in term of efficiency and ghost rate for various kind of analysis. Considering the much higher track density due to higher luminosity in Upgrade 2, the first results look very promising: efficiency $93.2 \pm 0.3 \%$, ghost rate $17.3 \pm 0.4 \%$ compared to Upgrade 1 (efficiency $96.8 \pm 0.5 \%$ and ghost rate $12.7 \pm 0.8 \%$). Performance numbers for different luminosities are obtained by means of the same algorithm and using Monte Carlo samples of the same event type.

Momentum and timing information were also investigated. From the results previously showed, efficiency and ghost rate are slightly improved. These approaches should be better explored and studied. To do so, one of the next steps is for sure to review a technique to reduce the ghost rate. A first test was made by using a threshold procedure to reject some of the wrong matches (mainly coming from Velo-UT segments not reaching the Tstations).

The next stage of this study should focus on how to improve the straight track model approximation. More hit information can be used from the tracking detectors to reconstruct a curved trajectory.
Bibliography


[6] Irene Cortinovis, Project and Presentations for LHCb Upgrade 2 group (Mighty Tracker)
Appendices
Appendix A

Sigma evaluation

Figure A.1: Sigma calculation by considering the standard deviation of the real distribution of predicted - measured variables for the position related $\chi^2$ term. The top plots are the x and y distributions while the bottom one the x and y slopes distributions.