Study of the LHCb pile-up trigger and the BsJ/ decay
Zaitsev, N.Y.

Citation for published version (APA):

General rights
It is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), other than for strictly personal, individual use, unless the work is under an open content license (like Creative Commons).

Disclaimer/Complaints regulations
If you believe that digital publication of certain material infringes any of your rights or (privacy) interests, please let the Library know, stating your reasons. In case of a legitimate complaint, the Library will make the material inaccessible and/or remove it from the website. Please Ask the Library: http://uba.uva.nl/en/contact, or a letter to: Library of the University of Amsterdam, Secretariat, Singel 425, 1012 WP Amsterdam, The Netherlands. You will be contacted as soon as possible.
As a by product the pile-up detector and trigger algorithm can be used to monitor the luminosity of the LHC machine. In this chapter we investigate this use of the pileup detector. The luminosity monitoring depends on the feature that the pile-up algorithm is able to classify bunch crossings according to the number of inelastic interactions that have occurred. The mean number of interactions per bunch crossing depends on the luminosity and hence the distribution over the categories zero - one - more interactions also varies with luminosity.

In view of the large number of interactions per bunch crossing and the fact that the bunch crossings always involve the same bunches\(^1\), it is in principle possible to determine the luminosity at the single bunch crossing level. The monitoring of the luminosity for individual bunch crossings is necessary as the bunch to bunch fluctuation (up to 10\%) leads to a non-linear correction factor due to the Level-0 acceptance rate. For a precision measurement of the absolute luminosity this factor has to be known. Possible systematic effects and calibration procedures are described.

17 Introduction

17.1 Method

The measurement of the luminosity and its monitoring are necessary:

1. for a better control of the stability of the trigger and DAQ systems of the experiment;
2. for the measurement of absolute cross sections and branching ratios.

It can be done by using the pileup detector and trigger algorithm described in the previous chapter. The detector is capable of classifying bunch crossings (BC) according to the number of interactions. A Poisson distribution:

\[
P(n) = \frac{\mu^n}{n!} e^{-\mu}
\]

\(^1\)Due to the equal length and the fixed radio-frequency of the two accelerator rings a bunch will always meet the same opposite bunch. This creates 2652 individual bunch crossings.
The pile-up detector as a luminosity monitor

describes the probability of \( n \) interactions to occur. The average number of interactions per BC, \( \mu \), is proportional to the luminosity, \( L: \mu = \sigma_{\text{det}} \cdot L \), where \( \sigma_{\text{det}} \) is the cross section seen by the detector. Hereafter we will call \( \mu \) the "relative luminosity".

The pileup detector is able to classify BC’s in three different classes: bunch crossings with zero interactions (\( N_0 \)), with a single interaction (\( N_f \)) and with multiple interactions (\( N_X \)). Because of the high bunch crossing frequency at the LHC it is possible to collect large statistics for each of these classes in a very short time. In particular, at the average luminosity of 2 \( \times 10^{32} \) cm\(^{-2}\) s\(^{-1}\) the rate for classes \( N_0, N_f \) and \( N_X \) will be 18 MHz, 9.3 MHz and 3 MHz, respectively. This would, in principle, give within one second a 0.1\% statistical accuracy in measuring the luminosity.

17.2 Analytic approach

In this analysis we consider four estimators of the relative luminosity \( \mu \):

- **Ratio** estimator: \( \hat{\mu} = N_1/N_0 \)
- **ZeroEvents** estimator: \( \hat{\mu} = -\log (N_0/N_f) \)
- **NonZeroEvents** estimator, found as the minimum of the \( \chi^2 \):
  \[
  \chi^2 = \frac{(\varepsilon_i - \mu e^{-\mu})^2}{\Delta \varepsilon_i^2} + \frac{(\varepsilon_X - (1 - e^{-\mu}(1 + \mu))|^2}{\Delta \varepsilon_X^2} \tag{39}
  \]
- **FullSample** estimator, found as the minimum of the \( \chi^2 \):
  \[
  \chi^2 = \frac{(\varepsilon_0 - e^{-\mu})^2}{\Delta \varepsilon_0^2} + \frac{(\varepsilon_1 - \mu e^{-\mu})^2}{\Delta \varepsilon_1^2} + \frac{(\varepsilon_X - (1 - e^{-\mu}(1 + \mu))|^2}{\Delta \varepsilon_X^2} \tag{40}
  \]

where \( \varepsilon_i = N_i/N_f \). \( N_i \) is the number of BC classified in class \( i \), and \( N_f \) is the total number of BC’s considered. The fractions \( \varepsilon_i \) follow multinomial distributions, since \( N_0 + N_1 + N_X = N_f \). Therefore, the errors are given by \( \Delta \varepsilon^2_i = N_f(N_f - N_i)/N_f \).

The errors on the last two luminosity estimators are given by:

\[
V[\mu] = 2 \left( \frac{d \chi^2}{d \mu^2} \right)^{-1}.
\]

Direct error propagation yields the errors for the first two estimators. The uncertainties are all proportional to \( \sqrt{1/N_f} \). The only difference is the proportionality constant which depends on the information used.

The precision with which the estimators determine the luminosity varies. The Ratio estimator has the worst precision whereas the FullSample estimator has the best. Figure 65 shows as a function of the luminosity the time necessary to obtain a precision of 0.5\% on the relative luminosity for a single bunch crossing. For the luminosities used by LHCb this precision is reached for the Ratio estimator within 20 seconds. The singularity at \( \mu = 0 \) for the Ratio estimator is due to the fact that the relative error for this estimator behaves as \( \sqrt{1/N_f} \sim \sqrt{1/(\mu \tau)} \) as \( \mu \to 0 \).

Asymptotically the FullSample and NonZeroEvent estimators are identical, as the zero event class vanishes as \( \mu \to \infty \).
The pile-up detector as a luminosity monitor

Figure 65: Calibration time necessary to determine the relative luminosity for one bunch crossing with a statistical accuracy of 0.5%. The dashed line corresponds to the average luminosity and the solid line to the maximum luminosity allowed at the LHCb. Lines represent (from top to bottom) four estimators: Ratio, ZeroEvents, NonZeroEvents and FullSample.

It should be mentioned, that Figure 65 only gives the statistical accuracy. Systematic effects may be important and indeed it will turn out that the ZeroEvent estimator taking into account both statistical and systematic contributions to the error has the best performance.

18 Systematic effects

Before embarking on the study of the systematics of the luminosity determination two comments are in order:

- The determination of the absolute luminosity requires the knowledge of the acceptance of the pile-up detector for the ‘known’ inelastic cross section. This is discussed at the end of the chapter. Since the acceptance is independent of the luminosity the determination of the relative luminosity, however, (bunch-bunch or run-run) is quite straightforward. The systematics of this relative measurement will be discussed.

- The determination of the luminosity from the number of interactions per bunch crossing is strictly only possible if the ‘real’ number of interactions is known. Migration from one class to another due to detector effects form the major cause of systematic uncertainty in the luminosity determination.

18.1 Monte Carlo model

To study the systematics of the luminosity determination, we performed a MC simulation of
The pile-up detector as a luminosity monitor

The response of the pile-up detector and algorithm to multiple interaction beam crossings. The detector simulation was identical to that of Chapter 4 with the exception of multiple scattering which is not switched on. The working point for the algorithm was that of Chapter 4 and corresponds to a single event efficiency of 95% and a double event retention of 12%.

The latest version of Pythia 6.134 [36] is chosen for the event generation in this study. The difference with version 5.7 which was used for the pile-up trigger performance is minimal.

Six event samples with 1 through 6 interactions per crossing were generated using Pythia. A sample with zero events was generated separately. In this case there are no interactions visible in the detector except for e.g. beam-gas and elastic interactions and the activity of the detector is the result of noise and other accidentals. In particular, we injected random noise into the system with a sigma of 3.9 keV (S/N=11) and requiring a 3σ threshold on the amplitude. In addition, we added on average 2 random hits in each detector to allow for background radiation tracks. The ZeroEvents sample and the six samples with pp interactions, were mixed in proportions corresponding to ten different Poisson probabilities with an average number of interactions per BC varying from 0.1344 to 1.344 with a 0.1344 increment.

18.2 ZeroEvents estimator

For this analysis we use the distribution of the largest peak (SI) of the pile-up algorithm shown in Figure 66. Three separate components can be distinguished in this distribution: a peak at small values of SI, which corresponds to ZeroEvents, a distribution, which is due to accepted diffractive events and a broad (up to SI=50-70) distribution, which is due to inelastic interactions. The diffractive component is hardly distinguishable in Figure 66 but clearly present when comparing it to Figure 67 where diffraction is switched off. The difference is highlighted by the dashed line in Figure 66.

To extract the ZeroEvents component we fit therefore the spectrum of Figure 66, with the following three contributions:

1. A gaussian distribution centered at SI=0 with a width of σ₀ = 0.592 ± 0.001, corresponding to the ZeroEvent category, G₀.
2. A gaussian distribution describing the response to accepted diffractive events, G₁.
3. A broad distribution due to inelastic events. From our Monte Carlo study this distribution is well described by a Γ (Gamma) distribution:

   \[ \Gamma(\mu, n, b) = (s_1)^n \cdot e^{-s_1}/\Gamma(n) \]

   For all values of the luminosity this gives a good description of the SI distribution of the inelastic component (see Figures 66 and 67).

In our simulation the shape of the ZeroEvents distribution is calibrated with the sample of ZeroEvents only (200k events). In the LHCh experiment it will be possible to determine this distribution from events recorded during unpaired bunch crossings, which occur in 25.6% of all bunch crossings. This procedure we call G₀-calibration.

By fitting the SI distribution to the sum of these contributions, f(SI):

\[ f(SI) = A₀ \cdot G₀(0, \sigma₀) + A₁ \cdot G₁(0, \sigma₁) + A₁ \cdot \Gamma(\mu, n, b) \]  \hspace{1cm} (41)

where σ₀ is obtained from the G₀-calibration, the ZeroEvent component can be obtained as the integral of A₁ \cdot G₁(0, \sigma₁). The relative luminosity, \( \mu \), is directly extracted from this number (A₁) using ZeroEvents estimator (given in section 17.2).

From the above analysis we obtain a value of \( \mu \) (\( \mu \)-measured) which can be compared with the
The pile-up detector as a luminosity monitor

**Figure 66**: Distribution of largest peak size. Diffractive events are roughly indicated by dashed line. The inserted is a blown up part of this distribution for $0 < S_j < 10$. Three lines represent the luminosities (from up to down) $5, 2.5, 0.5 \times 10^{32} \text{cm}^{-2}\text{s}^{-1}$.

**Figure 67**: Distribution of largest peak size. Diffractive events are switched off.

The input value of $\mu$ (\(\mu\)-generated). The difference between these two values, $\Delta \mu$, shows a systematic shift for these samples when the diffraction is switched on (Figure 68). This shift is due to the low acceptance for diffractive events, see Table 14, which makes it difficult to properly account for the diffractive contributions. This leads to an additional contribution to the ZeroEvents sample (or $A_0$). This additional contribution from diffractive events changes with luminosity. Indeed, if we switch off the diffraction there is no shift at all (see Figure 67, lower curve). The relative shift, $\Delta \mu/\mu$, decreases with increasing luminosity because the probability of a non-accepted diffractive event is decreasing faster than for a Zero Event.

This effect is described by the following formula:

$$\tilde{P}_0 = P_0 + \sum_{n=1}^{\infty} \alpha_n P_n(\mu)$$

(42)

where $\tilde{P}_0$ is the estimate of the ZeroEvents probability, $P_n$ are Poisson probabilities to have $n$-interactions in one BC and $\alpha_n$ is the fraction of such BC's identified as ZeroEvent. Extrapolating from present data (see review in [42]) indicates that the total cross section can consist of 30±5% of elastic and 10-20% of diffractive events (keeping the inelastic part at the 50-60% level)\(^*\). Pythia 6.134 with default settings gives an inelastic cross section of 55 mb and

\(*)$The large uncertainties in these numbers are mostly coming from the incompatibility of two direct measurements at Tevatron energies ($\sqrt{s}=1.8 \text{TeV}$) performed by E710 [43] and CDF [44]. The situation is expected to improve as CDF will repeat the measurements at higher energy after 2001.

**Systematic effects**

90
The pile-up detector as a luminosity monitor

![Graph](image)

**Figure 68:** $\Delta \mu/\mu$, the upper curve with diffraction included, the lower curve when the diffraction is off in the event generator.

**Figure 69:** $\Delta \mu/\mu$ as a function of $\mu$ including shift correction.

<table>
<thead>
<tr>
<th>geometrical acceptance</th>
<th>elastic</th>
<th>single diffractive</th>
<th>double diffractive</th>
<th>inelastic</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.0%</td>
<td>46.7%</td>
<td>55.8%</td>
<td>99.94%</td>
</tr>
</tbody>
</table>

**Table 14:** The geometrical acceptance for different event categories is given. The geometrical acceptance is defined as the fraction of events having at least one track in both wheels of the pileup detector. All digits are significant. Pythia 6.134 is used.

A diffractive cross section of 25 mb with a total cross section of 102 mb. The geometrical detector acceptance for diffractive events is $\leq 50\%$ (Table 14), therefore, they will contribute at $< 12\%$ level. Indeed, fitting $\Delta \mu/\mu$ with equation 42 we find that single diffractive events are the only cause of the shift. The coefficient $\alpha_i=0.094\pm0.002$ agrees with our rough estimates. The coefficients $\alpha_n$ for $n>1$ are equal to zero within errors. This can be explained by the fact that a double 'diffractive+inelastic' event will be seen by the algorithm as a single inelastic event and will contribute to the inelastic part of the $S1$-distribution. From this analysis it follows that we can correct for the shift using equation 42 with only $\alpha_i\neq 0$ (see Figure 69). Terms with $n>1$ may start contributing to the shift at higher luminosities like those foreseen at ATLAS or CMS.

Another possible source of systematics is due to the $G_0$-calibration. The change in the measured relative luminosity is shown in Figure 70. The upper/lower curves indicate the shifts in the measured luminosity, induced by a change of the value of $\sigma_0$ up/down by 1%. As the calibration of $\sigma$ can be done much more precisely and its precision is limited by statistics only this systematic error will be kept well below 1%. It is important to notice that the $G_0$-calibration can be done very precisely for any function describing the first term in (41).

In this analysis we presented only the results using the *ZeroEvents* estimator for the luminosity. For the other estimators, which rely on the selection of events with a single
The pile-up detector as a luminosity monitor

**Figure 70:** The relative shift of the measured luminosity, $\Delta \mu / \mu$, as a function of luminosity. Three different cases illustrate the possible systematic effects due to a poor $G_0$-calibration. The statistical error of 0.1% can be achieved in less than 1 sec. An over- and underestimation of 1% as shown in this plot therefore represents a very pessimistic situation. Diffraction is switched off.

interaction ($\varepsilon_1$) we should use in addition the second peak ($S_2$) distribution. The analysis of $S_2$ is more difficult as the efficiency in finding the second peak depends on detector alignment, acceptance and beam position. This makes the correction procedure which relies heavily upon the Monte Carlo simulation much more complex. Because of the complexity of our simulation model no conclusions can be drawn for other than the ZeroEvents estimator about the level of possible systematic errors.

We can conclude from this study that the pile-up detector and algorithm can provide a measurement of the relative luminosity. In view of its simple control of systematic effects the best estimator is the ZeroEvents estimator. The precision of this method is limited mainly by the acceptance of the detector for diffractive events. The shift in $\Delta \mu / \mu$ introduced is $\sim 10\%$ but the relative luminosity varies only by $\sim 2\%$ over the luminosity range expected for the LHCb experiment. Even with a relatively poor knowledge of the diffractive cross section corrections can be made such that the level of accuracy improves to $\leq 1\%$.

**18.3 Absolute normalization and total cross section measurement**

In this section methods are reviewed, which could be used by LHCb to determine the absolute normalization. Interested readers are referred to respective references for details.

To determine the absolute luminosity a measurement of the detector constant, $k^D$, is required. It is given by:

$$\mu^D = L \cdot \sigma \cdot k^D,$$

where $L$ is the luminosity, $\sigma$ is the total cross section and $\mu^D$ is the average event rate observed by the detector.
The pile-up detector as a luminosity monitor

Van der Meer method

The van der Meer method [45] was invented and used at the ISR for total cross section measurements. The cross section seen by the detector, \( \sigma \cdot k^p \), is calibrated by separating the beams vertically, and measuring the rate in the detector as a function of the separation. The ISR had continuous beams, therefore, a one-dimensional scan was sufficient. In contrast, the LHC beam has a bunch structure. This requires at least a scan in two dimensions: perpendicular and longitudinal. It was found [46] that also an additional scan in time is necessary. Due to this increased complexity \(^3\) the measurement becomes less reliable. The ATLAS collaboration has estimated [47] the precision of this method to be at best 8\%.

Normalization to TOTEM

The TOTEM [42] experiment will measure the elastic, diffractive and inelastic cross sections each with 1-2\% precision. Angular track distributions will be measured by TOTEM. Tuning Monte Carlo distributions (diffractive+inelastic part) to these measurements will allow a reasonably precise determination of \( k^p \). Similar measurements done by CDF and DO suggest that the normalization precision can be as low as 5-6\%. The largest systematic effect is due to the uncertainty in the total cross section measurement (see footnote on page 90). The systematic error from the luminosity detector itself is at the level of \( < 2\% \).

Normalization to known processes

In LEP experiments the cross section for (electromagnetic) Bhaba interactions was measured for luminosity calibration. A 0.1\% precision was achieved.

In \( pp \) interactions the QCD predictions for particular processes are less precise. There is a proposal, however, of using the W production cross section for normalization. Theoretical uncertainties of \( pp \rightarrow WW \rightarrow l\ell \) are at the 1\% level. Central detectors at the Tevatron and the LHC intend to use this process for luminosity calibrations [47].

Due to the large mass of the W the acceptance of LHCb for this process is small thus reducing its usefulness. Inclusive \( b\bar{b} \)-production (\( pp \rightarrow b\bar{b} \rightarrow \mu\mu \)) which also has a \( \sim 1\% \) theoretical uncertainty could provide an alternative for LHCb. The acceptance for this process is large while the experiment has an efficient double muon trigger to select these events. This makes this process a very promising one for absolute cross section normalization at LHCb.

A potentially large source of systematics in absolute luminosity measurements is the data acquisition. Because of the fixed bandwidth of the Level-0 trigger (1 MHz), the non-linear dependence of the trigger acceptance on the p-cuts and fluctuations at the bunch-bunch level of up to 10\% \(^4\) the event loss is also a non-linear function of both the average luminosity and the fluctuations with respect to its average value. It is estimated that neglecting the above mentioned fluctuations may lead to a systematic shift in the measured absolute luminosity value which varies from 2\% to 5\% within the LHCb luminosity range \( \langle 5 \cdot 10^{33} \text{ cm}^{-2}\text{s}^{-1} \rangle \). The length of readout buffers and their readout speed are estimated to cause a 1\% loss of events. These systematic effects will be corrected for in the normalization procedure.

\(^3\) The van der Meer method only uses a 1D convolution integral, while the LHC will require a 3D convolution integral.

\(^4\)This value is observed at other hadron accelerators like the Tevatron and HERA. The fluctuations are due to injectors.

Systematic effects
The pile-up detector as a luminosity monitor

19 Summary

The pileup detector can serve not only as a device for triggering on single interaction events, but also as a luminosity monitor. We estimate that the precision in determining the relative luminosity (event rate) is about 0.5%. This precision can be achieved at the single bunch crossing level after 20 seconds of data collection assuming 2652 BC's at IP8.

Several estimators of the luminosity have been considered. The best estimator from a statistical point of view uses all classes of interaction multiplicities (FullSample). In real experimental conditions, however, the ZeroEvents estimator gives the most reliable measurement. The analysis strategy for this sample was explained in detail. It was shown that the variation of the measured luminosity value does not exceed 2%, while after correction this variation can be kept at 0.5%. Various experimental effects can be accounted for by the G_0-calibration.

The low acceptance of diffractive events causes the most important bias in the relative and absolute luminosity measurements. We show that using simple assumptions it can be properly accounted for and allows this systematic error to be kept below 0.5%. Systematic effects due to the trigger and data acquisition will cause shifts from 2-5%. These can be taken into account by the normalization procedure.

The possible determination of the absolute luminosity is discussed. Experience of CDF and D0 suggests that the measurement of the absolute luminosity can be done with 5-6% precision and better.