13 Luminosity measurement

13.1 Introduction

Luminosity L relates the cross-section σ of a given process to the corresponding event rate R:

$$R = L \times \sigma . \qquad 13\text{-}1$$

Therefore, luminosity is by definition a process-independent quantity which is completely determined by the properties of colliding beams. Typically a 5–10% precision for the luminosity determination is assumed for measurements in ATLAS, as obtained in previous and existing hadron-collider experiments. However, there may be a few cases which would benefit from a luminosity precision of 1–2%. The possibilities of achieving a precise luminosity determination in ATLAS are therefore also being explored.

Luminosity measurement and monitoring are needed for several purposes with somewhat different requirements. Clearly, for physics analyses, one requires as precise as possible a measurement of the integrated luminosity, used to convert an observed number of events to a cross-section. However, one may need measurements of the instantaneous luminosity, possibly bunch-by-bunch. Such measurements might be needed, for example, when correcting for the effects of pile-up on physics measurements. In addition to following the luminosity evolution for physics-analysis purposes, for which a very fast response time may not be required, information may be needed to give fast feedback for beam tuning.

The collider luminosity can be expressed in terms of the beam parameters. For the LHC [13-1] with a small crossing angle and bunched beams, the formula reads (assuming Gaussian bunch shapes):

$$L = F \frac{f \sum_i N_1^i N_2^i}{4\pi \sigma^*_x \sigma^*_y} , \qquad 13\text{-}2$$

where f = 11 kHz is the beam-revolution frequency, F = 0.9 is a factor which accounts for the non-zero crossing angle, N_1^i and N_2^i are the numbers of protons in the colliding bunches and σ^*_x and σ^*_y are the transverse bunch widths (assumed to be the same for all bunches) at the interaction point (IP).

Even if there are technical means to store high beam currents and to strongly focus beams, the collider luminosity cannot be arbitrarily increased due to the intrinsic beam dynamics, for example due to the defocusing in the electromagnetic field of the opposite beam. The ultimate LHC luminosity is usually parametrised as:

$$L = \xi F \frac{f N k_b \gamma}{r_p \beta^*} ,$$

where ξ = 0.0034 is the so-called beam–beam tune-shift parameter, k_b is the number of (equal) bunches, γ is the beam Lorentz factor, r_p is the proton classical radius, β^* = 0.5 m is the value at the IP of the amplitude function β. The nominal transverse beam size at the IP is 16 μm and can be calculated from $\sigma = (\varepsilon_n \ \beta/\gamma)^{1/2}$, where ε_n = 3.75 μm×rad is the normalised transverse beam emittance. The beam divergence at the IP is given by σ^*/β^* and, for the design LHC parameters [13-1], is equal to 32 μrad. After the first year of LHC operation, 16% of the nominal beam currents should be achieved for $\xi = 0.0021$ (and $\varepsilon_n = 1$ μm×rad) resulting in a peak luminosity of approximately 10^{33} cm^{-2}s^{-1}.

In general, one can distinguish between three types of luminosity measurement. In the first approach the rate for a process with a well known and sizable cross-section is accurately measured and the luminosity is calculated from Equation 13-1. This method is widely used at e^+e^- colliders by measuring QED Bhabha scattering (or at HERA using *ep* bremsstrahlung) and high precision can be reached. At hadron colliders the QED processes usually have very small cross-sections compared to the hadronic ones and the second method of calculating the luminosity from the beam parameters (using Equation 13-2, for example) is therefore often used. However, the typical precision with this last method is rather poor, about 5–10%.

The third method, utilising the optical theorem in high-energy scattering, is also used at least to calibrate the absolute scale of the luminosity measurement. In this case, the total rate of *pp* interactions, R_{tot}, as well as the rate of forward elastic scattering, dR_{el}/dt (t = 0), is measured and the luminosity is derived from the relation

$$L\frac{dR_{el}}{dt}\bigg|_{t=0} = R_{tot}^2(1+\rho^2)/(16\pi)\,. \qquad 13\text{-}3$$

Here ρ is the ratio of the real to imaginary part of the elastic forward amplitude. In this method a dedicated detector of protons which scatter at very small squared-momentum-transfers, t, is required, as well as a high and known efficiency for detection of inelastic *pp* interactions. Also in this case, the typical precision is only about 5–10%.

One can distinguish between luminosity measurement and monitoring. Measurements via the methods described above give an absolute determination of the luminosity. Other methods may, however, be used to monitor the luminosity and can be calibrated using the absolute methods. Such relative luminosity measurements provide a convenient way to follow the luminosity evolution during a given collider fill and also between different fills. An attractive possibility is to calibrate them under special, favourable beam conditions (*e.g.* low luminosity and high β^*), and then use them to determine the luminosity for normal running *(i.e.* at high luminosity).

13.2 LHC beam diagnostics

For a proper running of the ATLAS luminosity system and also to some extent of the main detector, a number of the LHC parameters should be continuously available and recorded. For example, the parameter list could contain: beam energy, bunch currents, beam orbits near the IP, coil currents for the low-β quadrupoles and nearby correction coils, vacuum conditions, beam-loss monitor data, beam-halo collimation data, and the beam size or transverse emittance. Two aspects of the LHC diagnostics are especially important for the luminosity determination: measurements of the beam currents and the beam orbit near the IP.

13.2.1 LHC bunch structure

The bunch configuration of the LHC beams is determined by the injection and extraction systems in the acceleration chain. According to the present design the bunches are grouped into ‘trains’ of 81 bunches, which in turn are grouped into 12 batches each containing three bunch trains. Most probably the bunch currents will not be very uniform; one may expect bunch-to-bunch variations of 10% or more. Additionally, some residual currents might be observed in the high-luminosity running in neighbouring RF buckets resulting in the so-called side- (or satellite-) bunches, 2.5 ns apart from the nominal ones.

13.2.2 Beam-line instrumentation

A system of beam-position monitors (BPMs) for the LHC is already well developed [13-2]. The expected BPM performance at full beam current is 10 μm resolution with 100 μm absolute-scale uncertainty in each of the horizontal and vertical directions. The orbit position can be determined separately for each bunch. Non-destructive beam-profile monitors will also be installed.

13.3 Luminosity measurement in ATLAS

In general there are three aspects of luminosity measurement in ATLAS.

- Providing final absolute integrated-luminosity values for use in offline analyses, for the full data sample and for selected periods. Also required are measurements of the average luminosity over a small time interval and for individual bunch crossings.
- Providing fast online luminosity monitoring, as required for efficient beam steering and for optimising the luminosity yield; a statistical precision of about 5% per few seconds and systematic uncertainties below ~20% are desirable.
- Fast checking of running conditions and beam-related backgrounds (also with the main detector in a stand-by mode), such as monitoring the vertex position (in particular its longitudinal coordinate), monitoring the temporal structure of the beams (satellite bunches, de-bunching), and monitoring the level of beam-related backgrounds (possibly including the use of special non-colliding *p* bunches).

Since there is probably no single experimental technique which can fulfil all of the above requirements, one has to consider a number of complementary measurements.

13.3.1 Absolute luminosity scale with the optical theorem

As discussed in Section 13.1, the luminosity can be obtained using the optical theorem from a simultaneous measurement of the total interaction rate and the rate of forward elastic scattering.

The main challenge of this method lies in the detection of the very forward elastically-scattered protons. The elastic cross-section for small $|t|$ scales as e^{bt} where $b \approx 20\ \mathrm{GeV}^{-2}$ at LHC energies [13-3] (see Figure 13-1). Of course, the protons scattered at zero-angle (or at $t = 0$) cannot be detected, but the degree of extrapolation should be minimised and the smallest possible $|t|$ achieved. Use of so-called Roman pots is a well established technique (proposed for the LHC by the TOTEM collaboration [13-4] for example) for the measurement of the forward protons. The detector sensitive edge can be located very close to the beam centre, only about 15–20 beam widths away. To a good approximation the minimum scattering angle of a detected proton is 15–20 times the beam divergence at the IP. For the design LHC parameters this corresponds to an angle of about 600 µrad, or to a minimum $|t| = (7000\ \mathrm{GeV} \times 0.0006)^2 = 16\ \mathrm{GeV}^2$, and a reliable extrapolation down to $t = 0$ is not possible. However, for the low transverse beam emittance expected at the LHC start-up and assuming special running conditions with $\beta^* = 50$ m, the minimum angle is 35 µrad and $|t|_{min} = 0.06\ \mathrm{GeV}^2$. This should give extrapolation uncertainties of a few per cent, although running with even higher β^* might also be necessary. Uncertainties in the geometrical acceptance of the detector, as well as of detector inefficiencies, will of course increase the error on the dR_{el}/dt (t = 0) measurement.

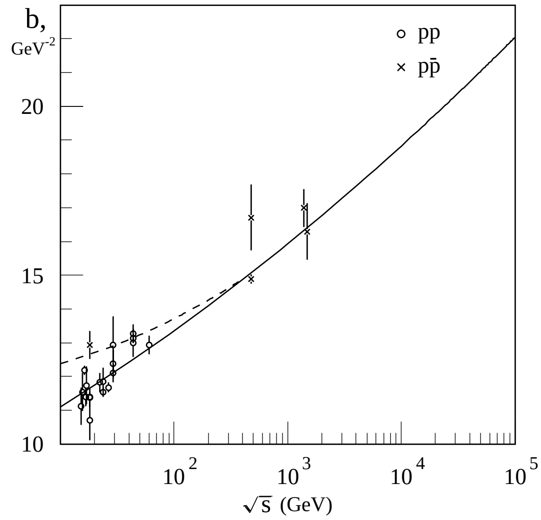

Figure 13-1 The *b* slopes of the *t* distributions at *pp* and $p\bar{p}$ colliders as a function of the center of mass energy.

In Equation 13-3, the total rate, which is dominated by the inelastic interaction rate, enters squared. In order to avoid large model-dependent corrections the detection efficiency for inelastic events should therefore be very high. The acceptance of the central ATLAS detectors is not sufficient, especially for low-mass diffractive events. Figure 13-2 shows the acceptance loss that results if the detector can only cover a fixed region of rapidity from η_{min} to η_{max}. From this figure, it can be seen that if additional forward detectors were installed, covering the pseudo-rapidity region $3.0 < |\eta| < 7.5$, the overall efficiency would be as high as 98%. Use of these detectors requires low-luminosity running to avoid event pile-up.

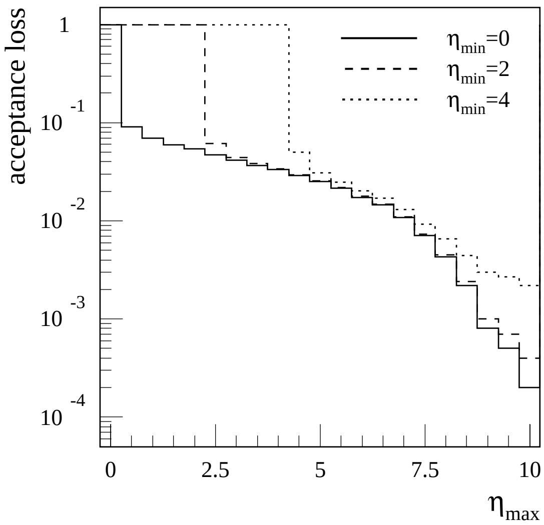

Figure 13-2 The inefficiency of tagging inelastic pp events as a function of pseudo-rapidity coverage. Only geometrical acceptance has been considered without allowing for magnetic field or detector inefficiencies.

Possible locations of the forward-tagging detectors needed for measuring the inelastic rate are at about 5 m and 16 m from the IP, very close to the beam pipe (see Figure 13-3). These forward detectors have to be radiation hard, but they might be simple, for example in the form of counters with full azimuthal coverage. Installation in the LHC tunnel of more counters, covering very extreme rapidities, will also be considered.

Finally, a measurement of the ρ parameter at the LHC is very difficult [13-4], although the uncertainty on its extrapolation to the LHC energy would result in a relatively small error of the order of 2% on the luminosity determination.

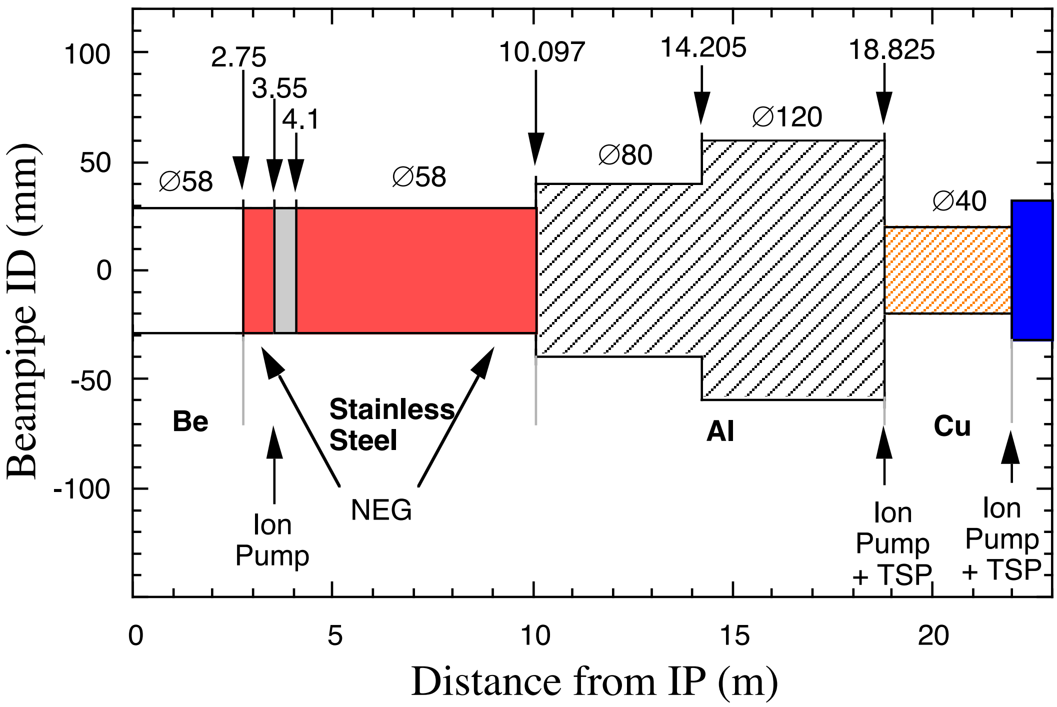

Figure 13-3 Shape of the ATLAS beam pipe showing the beam-pipe inner diameter as a function of the distance from the IP.

In summary, the method using the optical theorem requires additional dedicated detectors and special running conditions at a luminosity less than about 10^{32} $cm^{-2}s^{-1}$ to avoid pile-up, and achieving a precision much better than 5–10% seems difficult unless a very high and well understood efficiency for inelastic events as well as for low $|t|$ elastic scattering can be achieved.

If there were no detector for the elastically-scattered protons in the ATLAS IP, but there were a precise measurement of the total inelastic cross-section, σ_{inel}, from another experiment at the LHC, one can still determine the luminosity from a measurement of the rate of inelastic collisions, R_{inel}, using the relation $L = R_{inel}/\sigma_{inel}$. The precision of such a measurement would be given directly by the uncertainties on σ_{inel} and on the efficiency for counting inelastic events.

ATLAS is studying the option of adding the necessary detector systems. A decision will be made, after the completion of the feasibility study, whether to pursue an engineering study prior to proposing to the LHCC any addition to the ATLAS detector system.

13.3.2 Luminosity determination from the beam parameters

To determine the luminosity from the beam parameters (see Equation 13-2), one needs a good measurement of the lateral beam sizes as well as of the bunch currents. To obtain reliable σ^* values from the beam sizes measured outside the ATLAS IP one has to know precisely the β-function, but typically the uncertainty is up to 10%. This uncertainty could possibly be reduced if the beam divergence at the IP can be measured. In any case, with beam-profile measurements one should be able to verify the assumptions on the Gaussian shapes of the bunches (*i.e.* lack of long tails in the transverse distributions) and on the common width for all bunches.

Another way of measuring beam widths at the IP, which might be potentially more accurate, is the van der Meer method based on transverse beam scans. Originally [13-5], this was done by moving one beam vertically and at the same time recording the relative change of the rate of *pp* interactions. The value of the beam displacement required to decrease the rate to, for example, 50% of its peak value was a direct measure of the beam heights at the IP. The efficiency of counting *pp* interactions should not depend on the beam displacement.

In the case of the LHC, one has to perform scans in both transverse directions and the forward detectors could serve as monitors of the relative rate of *pp* interactions. Such scans are very difficult for low-β^* running since the beam–beam interactions are very strong and may affect the beam sizes while the scans are performed. Additionally, the beam size would be small (16 μm), *i.e.* comparable to the resolutions of the BPMs. Therefore, dedicated runs with large values of β^* (at least 50 m) are required. Another complication is due to the non-zero crossing angle which causes a longitudinal shift of the IP (and hence a change of the beam size since in a straight section $\beta = \beta^* + z^2 / \beta$), while one beam is moved transversely. Again the effect is only significant at low-β^* causing, for example, a 4% beam-size increase for a displacement corresponding to two beam widths.

For this method of luminosity measurement, a precise bunch-current measurement is essential. The ultimate precision will depend on the quality of the stored beams, *i.e.* to the level of the current in satellite bunches or in DC beam components (coasting, de-bunched beam). To avoid these effects, running at small beam currents with only a few bunches might be necessary.

In summary, use of the van der Meer method requires dedicated runs at high-β^* and very low luminosity ($< 10^{30}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$), and a precision of better than 5–10% on the luminosity determination seems difficult. Regular beam scans at high luminosity are unlikely to be feasible.

13.3.3 Luminosity determination from lepton pair production

The production of dilepton pairs via the process $pp \rightarrow ppll$ can be calculated precisely and might be used to measure the luminosity. Two possible methods are explored here: electron pairs produced with low invariant mass and very small p_T, and muon pairs of higher p_T, produced centrally. The former requires additional detector elements, and the latter, while it can be detected with the current ATLAS configuration, has a lower rate. In both cases, the backgrounds are serious and must be carefully studied.

13.3.3.1 Measurement of very forward two-photon production of e^+e^- pairs

The possibility of using two-photon processes for luminosity measurements at hadron colliders was first considered in [13-6]. The cross-section for very forward two-photon production of *ee* pairs can be calculated within QED to an accuracy better than 1%, and at LHC energies the production of high-energy pairs becomes sizeable. The main characteristics of the reaction $pp \to ppee$ are the very small (of the order of the electron mass) invariant mass and transverse momentum, p_T, of the produced pairs (see Figure 13-4). Inelastic two-photon production of *ee* pairs, where one or both protons break up, has a significantly wider distribution of pair p_T. For hadronic reactions, the typical energy scale is the pion mass or higher.

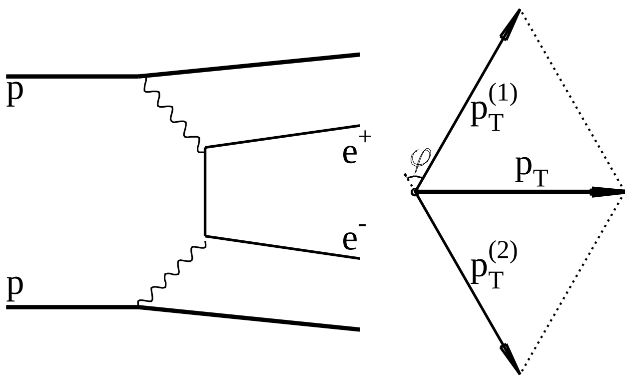

Figure 13-4 Feynman diagram and definition of the kinematical variables for the two-photon $pp \to ppee$ process.

Since the *ee* pairs are produced at almost zero polar angle, a small additional analysing dipole installed at about 15 m from the IP has been considered [13-7] to deflect the produced electrons and positrons into detectors outside the LHC beam-pipe without disturbing the LHC operation. For example, for a dipole bending power of 0.35 Tm and electron energies in the 5–20 GeV range, the detectors could be located about 20 m from the IP behind the TAS (TDS) shielding of the quadrupole inner triplet and a few centimetres from the beam, as shown in Figure 13-5. Provided the position and energy of the produced electrons can be measured with about 1% precision, resolutions of approximately 1 MeV could be achieved for measurements of the pair p_T and invariant mass. At high electron energies, the p_T resolution is limited by the beam divergence, $\sigma(p_T)$ = 40 GeV x 16 μrad ≈ 0.6 MeV. At low energies, the ultimate resolution on the invariant mass of a few MeV results from the deflection of electrons and positrons by the space-charge of the beams.

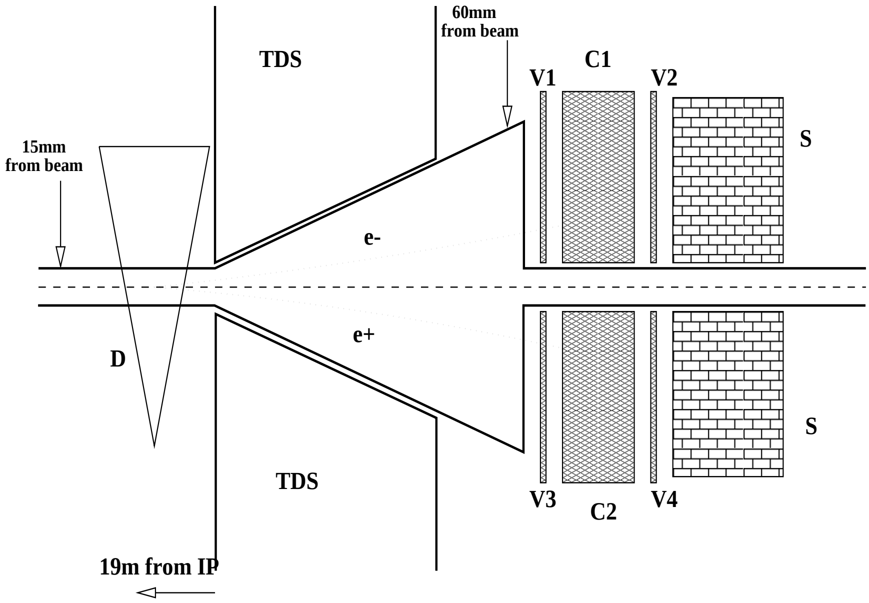

Figure 13-5 Sketch of a possible experimental setup for measuring forward production of *ee* pairs. TDS is the shielding of the inner triplet of quadrupoles, C1 and C2 are calorimeters with position detection, S is an additional shielding, D is a small analysing dipole and V1-V4 are veto counters.

A sizeable cross-section of more than 2 μb is expected for the following selection cuts:

1. electron energies: 5–20 GeV;
2. electron polar angles $\theta < 0.8$ mrad (corresponding to the beam pipe radius at 16 m from the IP);
3. *ee* pair invariant mass < 10 MeV;
4. *ee* pair $p_T < 10$ MeV;
5. veto on charged particles with $|\eta| < 7.6$ (see below).

Note that cut 5 requires the presence of additional detectors to cover the full rapidity range. Cross-section calculations for the kinematic cuts 1–4 were performed using the LPAIR program [13-8]. The dominant physics background is due to pion Dalitz decays and direct pair production in inelastic collisions labelled 'bremsstrahlung' in Table 13-1. The backgrounds were estimated using a modified PYTHIA generator, where direct pair production was simulated using

Table 13-1 Cross-section estimates in μb using analytic calculations for $pp \rightarrow ppee$ and a modified PYTHIA generator for bremsstrahlung pairs and Dalitz decays; The superscript (*) corresponds to the case where an additional cut $|\varphi| < 60^{\circ}$ was applied.

Cuts	Signal	Dalitz decays	Bremsstrahlung	Total background
1-4	2.27	2.26	0.90	3.16 (139%)
1-5	2.27	0.011	0.012	0.023 (1.0%)
1-4*	1.08	0.30	0.11	0.41 (38%)
1-5*	1.08	0.0009	0.0010	0.002 (0.2%)

the approximation of classical currents [13-9] and the momenta of the produced charged particles. After the selection cuts 1–4 there is still a significant difference between the two-photon process and the backgrounds in the p_T and acoplanarity-angle (φ) distributions shown in Figure 13-6. Note that the electrons are uncorrelated in φ; this is due to the extremely small transverse momenta (~15 MeV). The lack of correlation can be used either for extracting the signal in a fitting procedure or in making further cuts to suppress the backgrounds. For example, an additional cut on the φ angle can significantly improve the signal-to-background ratio, as shown in Table 13-1.

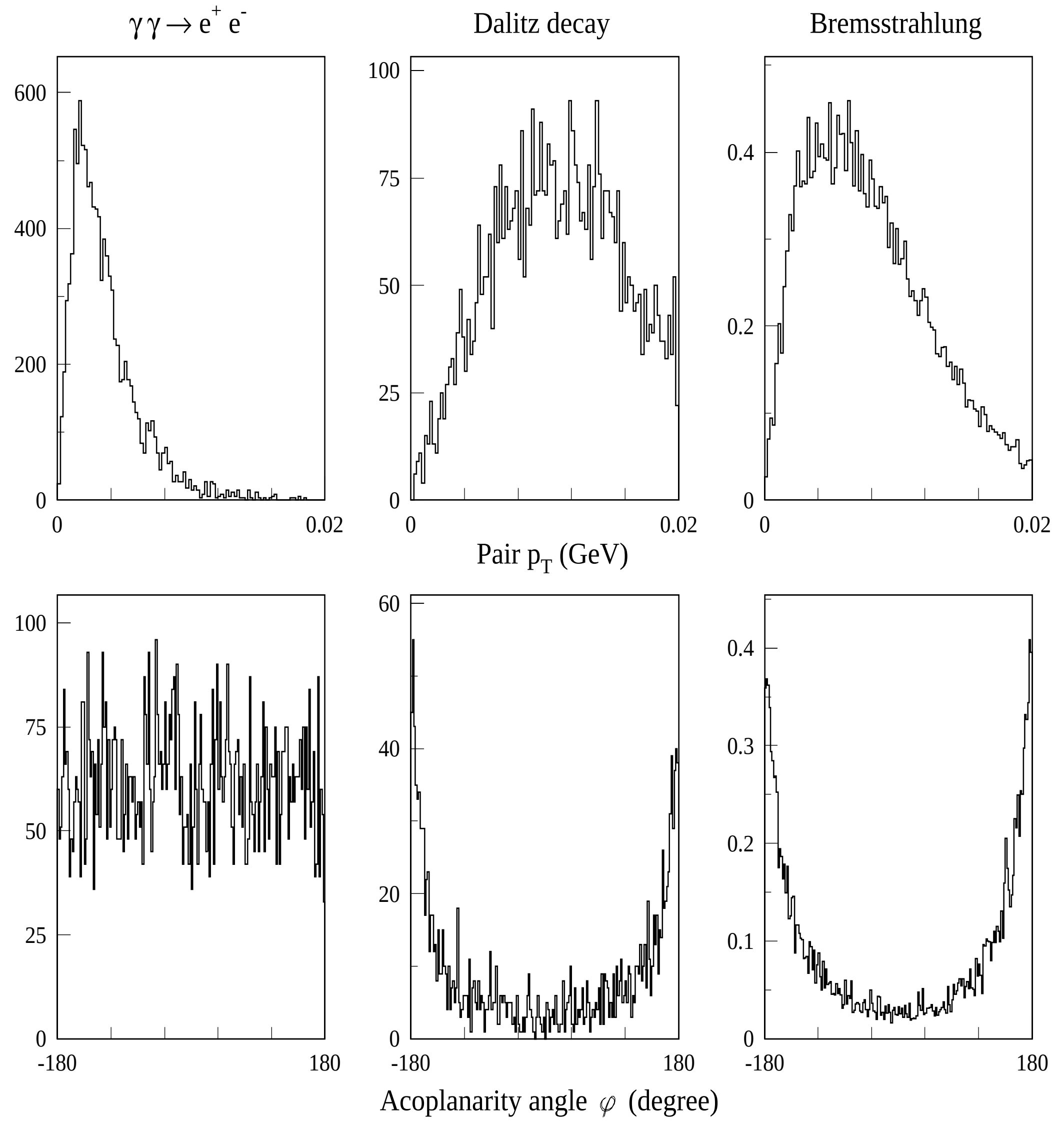

Figure 13-6 Distribution of p_T and acoplanarity angle φ for signal and background events (without detector smearing) after selection cuts 1–4.

At low luminosities the backgrounds can be reduced strongly by requiring no activity in the forward counters, *i.e.* by introducing condition (5), *i.e.* that no charged particles are produced above $|\eta| < 7.6$. One should note, however, that the calculations done so far neglected detector effects such as magnetic field and dead material and possible beam-related backgrounds.

A Monte Carlo simulation using the EGS4 package and a very simple model of electromagnetic-particle showering in ATLAS seems to indicate that the contribution of the secondary particles produced in electromagnetic showers is not very significant. Again, at low luminosities, requiring no activity in other ATLAS detectors would suppress this background even more.

More studies are needed to develop a suitable detection technique, but the potentially clear separation between signal and background makes this method an attractive option both for online and offline luminosity measurements. One should note that the analysing dipoles could become also a very useful tool for various kinds of systematic checks and luminosity-detector calibrations.

ATLAS is studying the option of adding the necessary magnet and detector systems. A decision will be made after the completion of the feasibility study, whether to pursue an engineering study prior to proposing to the LHCC any addition to the ATLAS detector system.

13.3.3.2 Measurement of central two-photon production of $\mu\mu$ pairs

The process $pp \rightarrow pp\mu\mu$ (related to the process discussed in Section 13.3.3 above), where the muons are produced at central rapidities, can be recorded using the standard ATLAS trigger and might provide an attractive method of offline integrated-luminosity determination [13-10]. The Feynman diagram of this two-photon process and the notations used are basically the same as for *ee* pair production shown in Figure 13-4. The invariant mass of the selected muon pairs is in the GeV range, but as for the forward *ee* pairs, the total transverse momentum of the pairs is very small. In contrast to the *ee* case, the muons have much larger transverse momenta and consequently are back-to-back in φ. The sharp peak expected in the acoplanarity-angle distribution at $\varphi = 0$ can be used to discriminate against background. Requiring, additionally, low particle multiplicity associated with the muon vertex, all sources of background can be reduced to acceptable levels. Signal extraction is performed by fitting the φ distribution which is not much affected by the detector resolution (unlike the distribution of the pair transverse momentum).

For centrally-produced muons, the elastic two-photon signal process has characteristic transverse momentum and acoplanarity values $p_T^{pair} \approx 5$ MeV and $\varphi \approx 2$ mrad. The corresponding values for Drell-Yan production are ≈300 MeV and ≈100 mrad, and those for muon pairs from quark decays are even higher. For all these sources of background, the observable particle multiplicity associated with the event vertex is typically greater than 12–14 particles. In the case of the inelastic two-photon processes $pp \rightarrow p^*p^*\mu\mu$, in which at least one proton dissociates, the observed particle multiplicity is low. However, the characteristic acoplanarity value is $\varphi \approx 50$ mrad.

Based on these considerations the following selection criteria were applied:

1. two muon tracks with opposite charges (measured in both the Inner Detector and the muon spectrometer, and triggered by the Muon System), with $p_T > 6$ GeV, and $|\eta| < 2.2$;
2. muon-pair invariant mass < 60 GeV;
3. p_T of the muons is required to be equal within 2.5σ of the p_T measurement uncertainty (typically about 1.5% for low p_T muons);
4. acolinearity angle $\Theta > 1°$, so that the muons are almost back to back;
5. χ^2 probability > 1% for the muon vertex fit;
6. no other reconstructed charged tracks originating from the muon vertex.

Criterion (1) is applied to satisfy the trigger; criterion (2) suppresses the background from Z decays; criterion (3) is related to the requirement that the pair p_T be small, but leaves the acoplanarity angle distribution unchanged for the final background subtraction; criterion (4) suppresses the cosmic-ray background; criterion (5) defines the event vertex and suppresses the background from heavy-quark decays; and finally, criterion (6) strongly suppresses backgrounds with a high particle-multiplicity. Criterion (6) could reduce the detection efficiency for the two-photon process due to pile-up effects. At a luminosity $L = 10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ the reduction is 2–3% for the expected longitudinal beam size of the LHC. For $L = 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ criterion (6) should be relaxed such that the reduction should not exceed 10%; this will have to be verified using experimental data.

The signal observability has been investigated using a particle-level Monte Carlo code with the detector properties parametrised according to the ATLAS specifications. The elastic two-photon processes were simulated with an approximate event generator developed for *ee* collisions [13-11]. This was adapted for *pp* scattering according to [13-12]. For the elastic two-photon process, its accuracy is about 1% for the kinematic domain of interest. The proton structure function W_2 used for the inelastic two-photon calculations was extracted from photo- and electro-production data [13-13]. The effect of resonances was taken into account. The predicted inelastic cross-section is greater than that of the LPAIR generator which uses approximate structure functions [13-14]. The event generation includes soft-photon emission which affects the observed distributions of φ and invariant mass.

The signal and background cross-section estimates are presented in Table 13-2 (the detection efficiency was not taken into account). The cross-sections are given for the narrow interval of acoplanarity angle $|\varphi| < 0.005$ containing about 50% of the signal. The background referred to as '2γ strong' is due to strong interaction between the protons in the two-photon process of pair production.

Table 13-2 Observable signal and background cross-sections for the two-photon production of muon pairs; σ_{kinem} and σ_{vertex} correspond to the selection criteria (1–4) and (1–6), respectively (see text).

Process	**σ_{kinem} (pb)**	**σ_{vertex} (pb)**
Signal	1.33	1.30
2γ inelastic	0.13	0.13
Drell-Yan process	3.8	0.04
Heavy quark decays	10	0.01
π, K decays	1.8	<0.001
2γ strong	0.04	0.04
Background total	15.8	0.22 (17%)

Figure 13-7 shows various distributions for the elastic two-photon process and dominant background processes, after applying the criteria 1–6, for an integrated luminosity of 10 fb^{-1}. Fitting the acoplanarity would determine the signal rate with a statistical error of 1.6% assuming a detection efficiency of 75%. Even if the background-to-signal ratio were increased by a factor of four to 0.68 the error on the signal would not exceed 2%. Note that the correlation in ϕ is much sharper for the signal than the background as can be seen from the expanded scale on Figure 13-7. In conclusion, the elastic two-photon production of muon pairs might provide the possibility of offline determination of the integrated-luminosity with a statistical accuracy of about 2% for

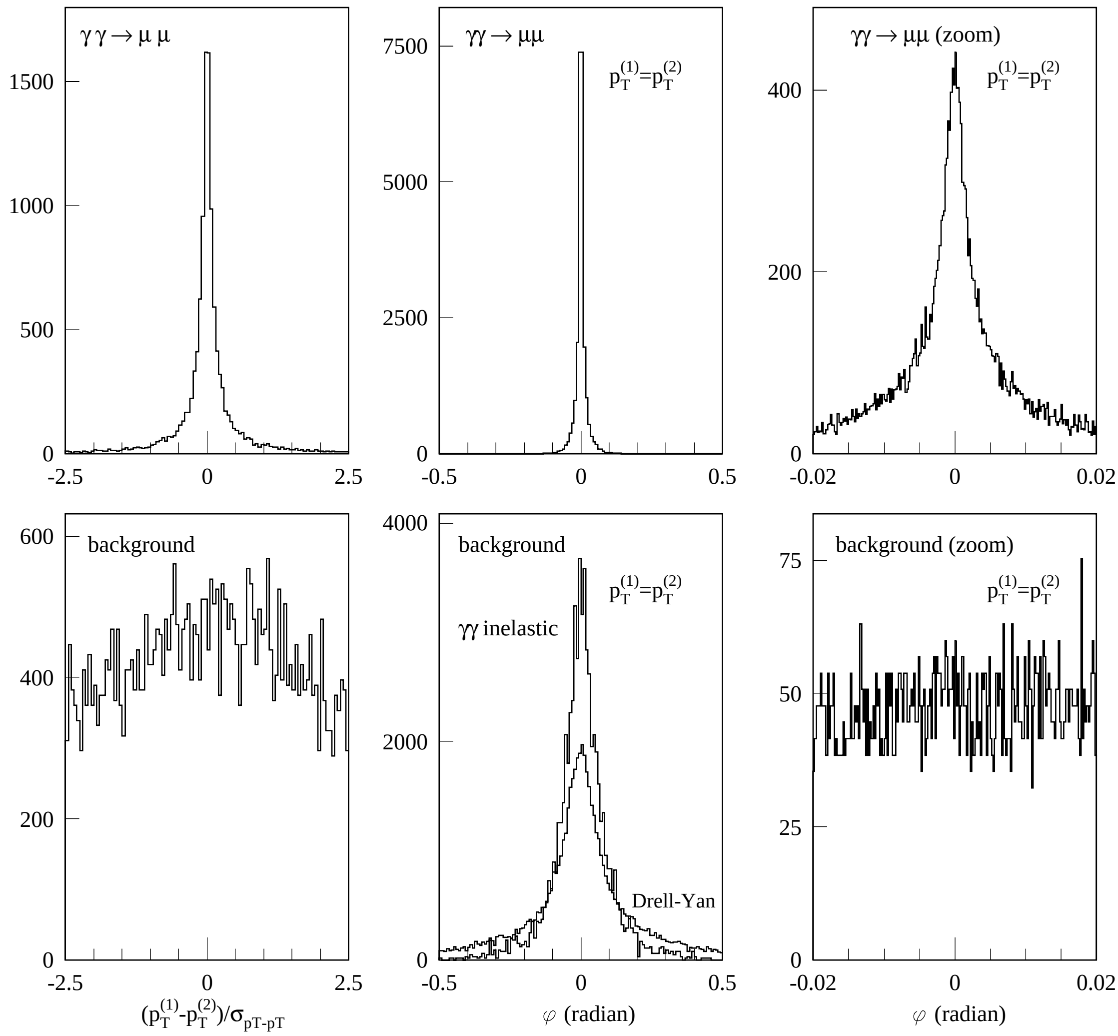

Figure 13-7 The distributions of the transverse momentum difference, normalised to the measurement error, (left) and acoplanarity angle (φ) (middle and right) between the two muons in exclusive two photon production of the muon pairs (top) and the major backgrounds (bottom), for an integrated luminosity of 10 fb^{-1}.

an integrated luminosity of 10 fb^{-1}. The background estimates rely on QCD calculations in regions where they have not been tested. In particular the modelling of the cuts may be deficient. It remains to be proven that the systematic uncertainties associated with these issues can be reduced to the 1% level. Furthermore, at high luminosity, pile-up will limit the effectiveness of the selection criteria.

13.3.4 Relative luminosity measurements

As a primary tool for fast online luminosity monitoring, small-area counters (to avoid event pile-up effects) located at large angles are considered. A possible candidate are the existing intermediate Tile Calorimeter scintillators [13-15] which are finely segmented (128 divisions in azimuthal angle and four in η) and cover $0.8 < |\eta| < 1.6$. The discriminated photomultiplier signals could be used in coincidence to build simple triggers for monitoring the *pp* interaction rate. The detector signals could also be used in complementary ways, *e.g.* for the measurement of hit rates in the smallest sections of the detector, for the measurement of energy flow in groups of these sections. However, one should note that these counters are not typical hodoscopes since there is a significant amount of dead material in front of them. Therefore, detailed Monte Carlo studies of preshowering effects and detector efficiencies have to be performed before reaching firm conclusions.

The measurement of high-voltage (HV) currents in the liquid Argon [13-16] and Tile [13-15] calorimeters provides another, largely pile-up insensitive, way of monitoring luminosity. For example, in the LAr calorimeter the current will be monitored in η–ϕ regions related to the segmentation of the HV system; there are seven η segments in the barrel, seven in the outer end-cap wheel and two in the inner end-cap wheel of the calorimeter. In azimuthal angle, the segmentation is 32 (128 in the inner wheel), with the two sides of the electrodes monitored independently. The expected current per HV channel at the nominal LHC luminosity varies from about 10 μA at $\eta = 0$ up to 50 μA at $|\eta| = 3.2$. Other sources of current are significantly smaller. A 1% non-linearity of the calorimeter response for high particle fluxes (corresponding to the nominal LHC luminosity) in the end-cap inner wheel was seen with a 2 m prototype tested in a beam. In future tests this effect will also be measured for the HV currents. Changes of the LAr calorimeter response due to temperature and impurity variations with time are expected to be small and slow. A periodic absolute cross-calibration of this method of luminosity measurement should be envisaged.

Last, but not least, measurements using the ATLAS detectors for processes with clear signatures and sizable cross-sections can also be used for relative luminosity measurements. The primary candidate is Z production with a rate for leptonic Z decays above 10 Hz at the nominal LHC luminosity, which corresponds to a 1% statistical uncertainty after about 20 minutes. Uncertainties in the QCD predictions for Z production imply that this method cannot be used for a precise measurement of the absolute luminosity.

13.3.5 Technical aspects

The data acquisition system of the luminosity monitor should be flexible enough to be able to provide the on-line data almost independently of the status of the main ATLAS detector (*e.g.* during beam steering / optimisation when the ATLAS data taking will be in a stand-by mode). It should be capable of storing large sets of calibration data and making fast online calculations.

The read-out and trigger electronics of the luminosity monitoring system (especially for large-angle counters) should allow for building (topologically) different trigger types, with different sensitivity to beam-related backgrounds or event pile-up. For a good control of beam-related backgrounds, special bunch configurations including non-colliding pilot bunches might be very useful. Practically all considered methods are affected to some extent by pile-up effects, therefore storing regularly a number of bunches (*e.g.* two colliding trains of 81 bunches) with 10–20% of the nominal current should be seriously considered. This would allow for both online and offline monitoring of the pile-up effects at high luminosities.

Since one expects significant variations of the luminosity per bunch, an online monitoring of the bunch-to-bunch luminosity is desirable. A possible option is to use the LVL1 Central Trigger Processor scalers [13-17]. These are able to measure the rate for each type of LVL1 trigger independently for each bunch crossing.

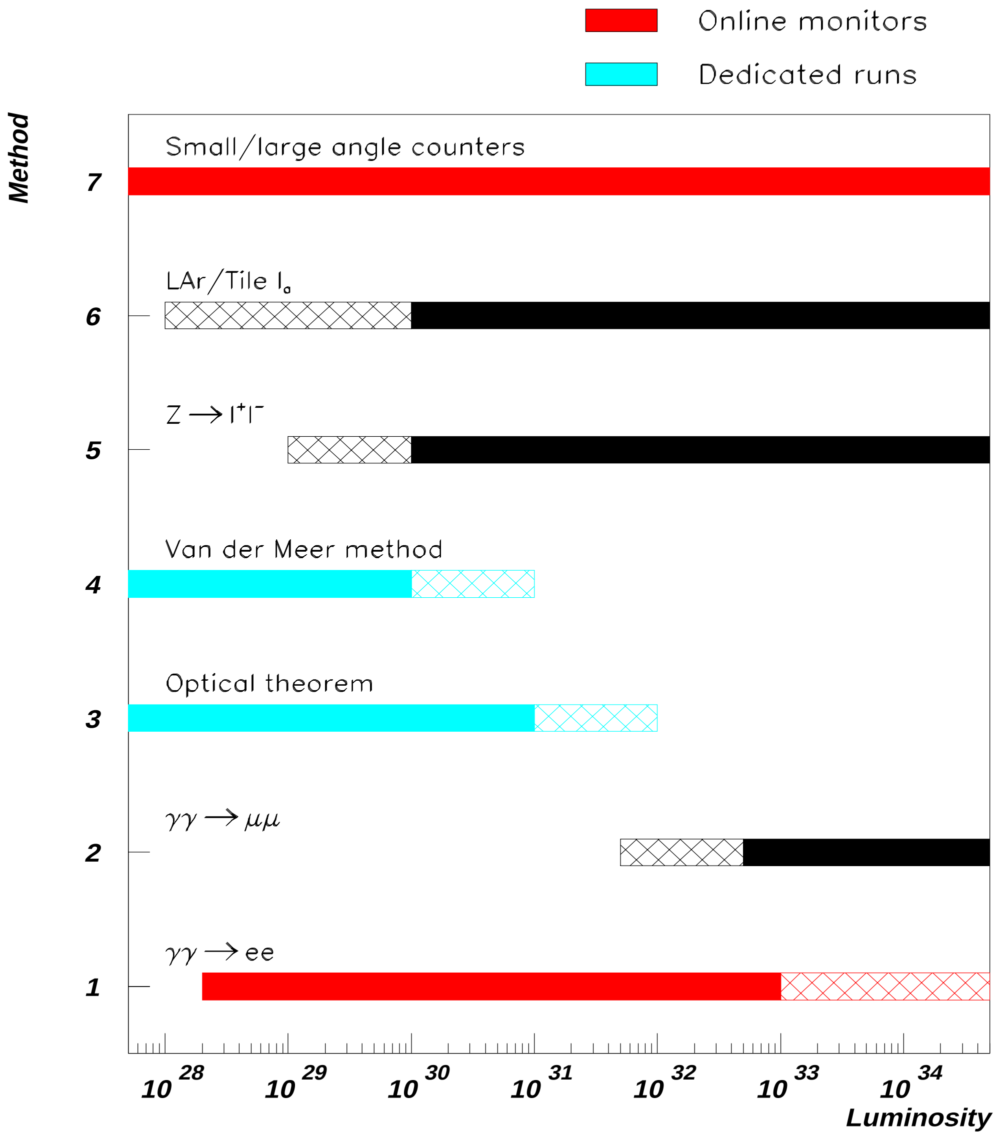

Figure 13-8 Diagram showing the range of applicability of the techniques of luminosity measurement and monitoring in ATLAS; hatched areas indicate luminosity ranges for which precision of a given method will significantly deteriorate. The top three methods are used for relative measurements only. The units are $cm^{-2}s^{-1}$.

13.4 Summary

To ensure reliable luminosity measurements both for high- and low-luminosity running, a number of complementary methods are needed. Figure 13-8 summarises the applicability of all techniques discussed in this chapter. It shows that, over the relevant range of LHC luminosities, redundant methods of luminosity measurement and monitoring should be possible.

Standard techniques based on the van der Meer method or on the optical theorem and the measurement of elastic and inelastic *pp* scattering, should the additional detector elements become available, are not applicable at the luminosities required for physics runs. Production of electron or muon pairs through the two-photon process might provide a precision luminosity measurement in ATLAS over the full range of luminosity. However, further studies of systematic effects, background conditions and detector issues are needed before reaching any conclusions. The technique with *ee* pairs would require additional instrumentation in the very forward regions. Measurements using Z decays and monitoring of the currents in the calorimeters will provide precise luminosity monitoring but cannot provide precise measurements of absolute luminosity.To reach a good understanding of systematic effects a number of dedicated runs with high-β^* beam optics and with very low beam currents might be necessary. For good control of beam-related backgrounds, special bunch configurations, including non-colliding pilot bunches might be very useful, as well as storing a number of bunches (e.g. two colliding trains of 81 bunches) with 10–20% of the nominal current for monitoring of the pile-up effects at high luminosity.

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