

Chapter 4

Luminosity Measurement

4.1 Run I Luminosity

The ATLAS Run I data were recorded from 2011 to 2012, with a center-of-mass collision energy of $\sqrt{s} = 7 \text{ TeV}$ in 2011 and $\sqrt{s} = 8 \text{ TeV}$ during 2012. Integrated luminosities of $L = \int \mathcal{L} dt = 5.46 \text{ fb}^{-1}$, and 22.8 fb^{-1} were delivered by the LHC in the two years, of which 5.08 fb^{-1} and 21.3 fb^{-1} were recorded by the ATLAS detector. The recorded luminosity accounts for the data acquisition inefficiency, as well as the warm start period, an interval of several minutes after the LHC has of stable beams during which the tracking detectors are ramped to high voltage and the pixel detector preamplifiers are turned on. After masking data recorded while one or more detector subsystems were not functioning properly, 4.57 fb^{-1} and 20.3 fb^{-1} of data are considered ready for physics analyses. The volume of delivered, recorded, and physics-ready data are shown as a function of time in figure 4.1a.

During Run I, the LHC was typically operated with 1368 bunches with a bunch spacing of 50 ns. The peak instantaneous luminosity reached values as high as $\mathcal{L} \sim 8 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$, corresponding to a peak average pileup value of $\mu \sim 37$. The distribution of pileup values in 2011 and 2012 data are shown in figure 4.1b.

4.2 Measurement Overview

The instantaneous luminosity at a pp collider is given by [1, 2]:

$$\mathcal{L} = \frac{R_{\text{inel}}}{\sigma_{\text{inel}}}, \quad (4.1)$$

where R_{inel} is the rate of inelastic pp collisions, and σ_{inel} is the pp inelastic cross section. For a storage ring with a revolution frequency f_r and n_b colliding bunch pairs, the instantaneous luminosity can be written in terms of the average number of inelastic pp collisions

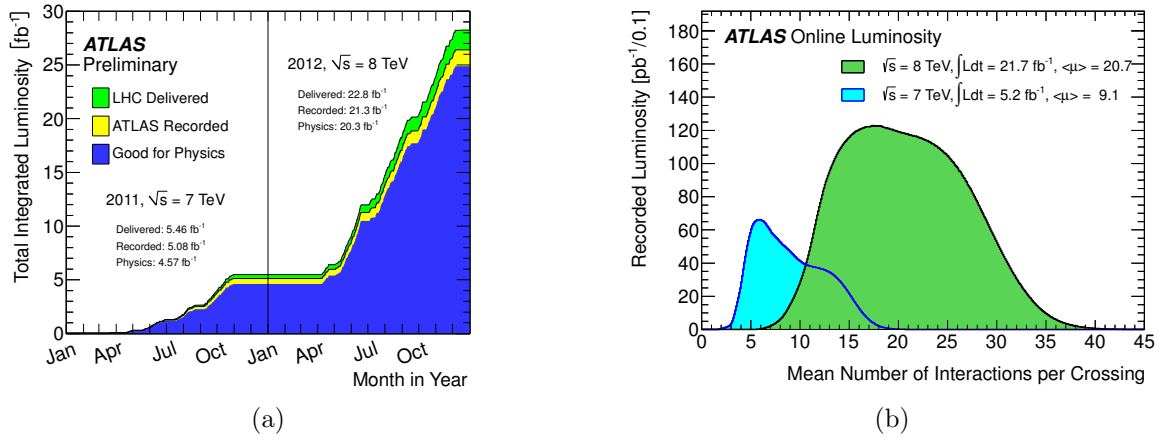


Figure 4.1: Left: The cumulative delivered, recorded, and physics-ready integrated luminosity versus time in 2011-2012. Right: Distribution of the number of interactions per bunch crossing in events recorded in 2011-2012.

per bunch cross, μ , as

$$\mathcal{L} = \frac{\mu f_r n_b}{\sigma_{\text{inel}}}. \quad (4.2)$$

The instantaneous luminosity is measured by ATLAS using several detectors and algorithms, which have some efficiency ϵ to detect a pp interaction and measure the *visible* number of interactions per bunch crossing, $\mu_{\text{vis}} = \epsilon\mu$. Defining the visible cross section to be $\sigma_{\text{vis}} \equiv \epsilon\sigma_{\text{vis}}$, the instantaneous luminosity as measured by a particular detector is:

$$\mathcal{L} = \frac{\mu_{\text{vis}} f_r n_b}{\sigma_{\text{vis}}}. \quad (4.3)$$

The visible cross section is a calibration constant for a particular detector, which is determined during dedicated calibration runs in which the luminosity is determined directly from the geometry of the beams. The calibration procedure is described in section 4.4.

4.3 Luminosity Detectors

ATLAS performs many redundant luminosity measurements using several detectors. The detectors fall into two categories. *Event counting* detectors have a binary response, returning a 0 or 1 depending on whether a bunch crossing satisfies a set of criteria defined to detect an inelastic pp collision. Such detectors essentially measure $p(0; \mu)$, the probability that an event falls in the zero bin of a Poisson distribution, from which the mean μ be calculated. *Hit counting* detectors, on the other hand, count some quantity proportional to the number of interactions in a given bunch crossing, such as the number of particles identified by a

particular detector subsystem. A hit counting measurement typically yields more information about an event at the cost of additional systematic uncertainties.

Ideally, a luminosity detector exhibits the following features:

- The efficiency of the detector should be insensitive to pileup. The visible cross sections are typically measured at $\mu \approx \mathcal{O}(1)$, while a typical data-taking run has $10 \lesssim \mu \lesssim 50$; it is essential that the visible cross section be constant across this range of pileup values.
- The efficiency of the detector should also be constant over long timescales.
- The response of the detector and the readout should be fast enough to provide a bunch-by-bunch luminosity measurement. As the LHC bunches are not identical, with different numbers of protons and emittances, it is useful to measure luminosity for each colliding bunch pair, as often as once every 25 ns. The colliding bunch pairs are labeled by the bunch crossing identification number, or BCID; consecutive BCIDs are separated by 25 ns.
- The efficiency should be high enough to yield sufficient statistics. The data are used in increments as short as 20 s, so the statistics collected over this time scale should be high enough that the total uncertainty is dominated by systematic effects. On the other hand, for event counting detectors, the efficiency should not be so high that the detector is saturated; the uncertainty on μ is large if $p(0; \mu)$ is too close to 0 or 1.
- The backgrounds should be low and understandable. Detectors can be sensitive to a wide range of phenomena aside from pp collisions, which should not be counted as luminosity. For example, some detectors observe a phenomenon called *afterglow*, a small amount of activity in the BCIDs immediately following a collision likely due to photons from nuclear deexcitations in the detector material. The afterglow background is proportional to the luminosity in the colliding BCIDs, and decays away with several time constants. Collisions between a beam and residual gas in the beam pipe, called *beam-gas interactions*, can also contribute a low level of background, and is estimated by observing non-colliding bunches passing through the interaction region.

The central value of the luminosity measurement is determined by the *beam conditions monitor* (BCM) [3], which fulfills most of these desired criteria. The BCM consists of eight diamond-based particle detectors, four on each side of the interaction point at $|z| = 184$ cm and $|\eta| = 4.2$. The detectors have a physical cross section of approximately 1 cm^2 and are arranged in a cross pattern, with two readouts corresponding to the vertical and horizontal pairs. The design purpose of the BCM is to monitor backgrounds and to trigger a beam dump if beam losses towards the inner detector become too high; accordingly, the detector has a very fast readout, and can provide a bunch-by-bunch luminosity measurement with a time resolution of ~ 0.7 ns. The luminosity is measured using event counting, and can be measured using any combination of the readouts. The configurations used require hits in

either the vertical pair (BCMV) or the horizontal pair (BCM_H), and either coincident hits on both sides of the interaction point (AND) or a single hit on either side (OR). The small size of the readouts leads to an efficiency of approximately 7% in the OR configuration, which allows for sufficient statistics without saturating the detector.

LUCID (LUminosity measurement using Cherenkov Integrating Detector) [4] provides a supplementary, bunch-by-bunch, event counting-based luminosity measurement. The detector consists of two sets of sixteen Cherenkov detectors surrounding the beam pipe at $z = \pm 17$ m, occupying the pseudorapidity range $5.6 < |\eta| < 6.0$. The Cherenkov detectors are polished aluminum tubes filled with C₄F₁₀ gas. The Cherenkov photons induced by charged particles traversing the gas are collected by photomultiplier tubes (PMTs) located at the far end of the tubes. Additional Cherenkov photons are produced in the quartz window separating the tube volume from the PMT. In this configuration, the typical single-particle yield is 60-70 photoelectrons due to photons created in the gas, and about 40 photoelectrons due to the quartz window. A hit is recorded if the PMT signal exceeds a preset threshold, corresponding to about 15 photoelectrons. However, the higher instantaneous luminosities due to the 50 ns bunch spacing led to saturation of the detectors, and hence on 30 July 2011, the gas was removed from the Cherenkov tubes to reduce the efficiency. The removal of the gas also improved the detector's stability and linearity with respect to pileup. Relative comparisons with other detectors were used to reestablish the detector calibration.

Several detector subsystems nominally designed for physics object reconstruction are also used for hit counting-based luminosity measurements. Algorithms using the tile calorimeter and the forward calorimeters (see section 3.2) determine the luminosity from detector currents proportional to the total particle flux in small regions of the calorimeters. The tile calorimeter algorithm monitors the PMT currents corresponding to a few selected cells near $|\eta| = 1.25$, where the highest sensitivity to changes in the luminosity is observed. Similarly, the forward calorimeter algorithm monitors the currents in the high voltage lines. In both cases, the detector response is too slow to provide a bunch-by-bunch measurement, and the current response is not sensitive to the low instantaneous luminosities during the dedicated calibration runs, requiring the calibration to be set using a relative comparison with LUCID. On the other hand, the detectors exhibit good linearity of response with pileup, and good short-term stability.

Finally, algorithms using the inner detector measure the luminosity by counting reconstructed tracks and vertices¹. The use of these higher-level objects confers certain benefits, such as low background rates and good long-term stability, at the cost of increased computational requirements, which limit the data rate to $\mathcal{O}(100 \text{ Hz})$. Further, pileup effects can be significant; in particular, the efficiency of the vertex counting algorithm varies by as much as 30% up to pileup values of $\mu = 30$, limiting its utility to data with low pileup.

¹Pixel cluster counting, used by the CMS experiment, was also considered, but was not commissioned due to the difficulty of the background subtraction.

4.4 Luminosity Calibration: van der Meer Scans

The visible cross sections for the detectors and algorithms described in section 4.3 are calibrated during dedicated runs called van der Meer (vdM) scans [5]. The calibration procedure uses the definition of luminosity in terms of the beam parameters, given for a single colliding bunch by:

$$\mathcal{L} = f_r n_1 n_2 K \int \rho_1(x, y, z, t) \rho_2(x, y, z, t) dx dy dz dt, \quad (4.4)$$

where f_r is the revolution frequency, $n_{1,2}$ are the number of particles in the colliding bunches, and $\rho_{1,2}(x, y, z, t)$ are the time- and position-dependent particle density distribution, normalized so that $\int \rho_{1,2}(x, y, z, t) dx dy dz = 1$. K is a kinematic factor,

$$K = \sqrt{(\vec{v}_1 - \vec{v}_2)^2 - \frac{(\vec{v}_1 \times \vec{v}_2)^2}{c^2}}, \quad (4.5)$$

which, in the limit $|\vec{v}_{1,2}| \rightarrow c$, reduces to $2c \cos \alpha$, where α is the crossing angle between the beams. To simplify the current discussion, the crossing angle is assumed to be zero, and the bunch densities are assumed to be functions of x , y , and $z \pm ct$, i.e. that the transverse bunch profiles are constant over the duration of the collision². The luminosity can then be expressed as:

$$\mathcal{L} = f_r n_1 n_2 \int \hat{\rho}_1(x, y) \hat{\rho}_2(x, y) dx dy, \quad (4.6)$$

where $\hat{\rho}_{1,2}(x, y)$ are the transverse particle densities, normalized to unity. Under the further assumption that the transverse particle densities factorize in the horizontal and vertical directions, $\hat{\rho}(x, y) = \hat{\rho}_x(x) \hat{\rho}_y(y)$, where $\hat{\rho}_x(x)$ and $\hat{\rho}_y(y)$ are also normalized to unity, the luminosity can be written as:

$$\mathcal{L} = f_r n_1 n_2 \Omega_x(\hat{\rho}_{x1}, \hat{\rho}_{x2}) \Omega_y(\hat{\rho}_{y1}, \hat{\rho}_{y2}), \quad (4.7)$$

where $\Omega_x(\hat{\rho}_{x1}, \hat{\rho}_{x2}) = \int \hat{\rho}_{x1}(x) \hat{\rho}_{x2}(x) dx$, and similarly for the y direction. As first proposed by van der Meer, the $\Omega_{x,y}$ parameters can be determined by measuring the interaction rate as a function of transverse beam displacement, $R_{x,y}(\delta)$. Without loss of generality, assume that beam 2 is displaced by δ in the x direction, while beam 1 is held fixed. Then, $R_x(\delta) = k \int \rho_{x1}(x) \rho_{x2}(x - \delta) dx$ for some constant k , and

²In particular, the *hourglass effect* is neglected. The collisions occur in a drift space, where the beams are focused, or squeezed, onto the interaction point. The transverse size of the beam in direction i as a function of z is given by $\sigma_i^2(z) = \epsilon_i \beta_i^* \left(1 + \frac{(z - z_i^w)^2}{\beta_i^{*2}}\right)$, where ϵ_i is the transverse emittance, z_i^w is location of the optical waist, and β_i^* is the betatron function at $z = z_i^w$. The effect is significant when $\beta_i^* \lesssim \sigma_z$; during the vdM scans, $\sigma_z \approx 50$ mm, while $\beta^* = 1.5$ m-11 m, and hence the hourglass effect is neglected.

$$\frac{R_x(0)}{\int R_x(\delta) d\delta} = \frac{k \int \rho_{x1}(x) \rho_{x2}(x) dx}{k \int \int \rho_{x1}(x) \rho_{x2}(x - \delta) dx d\delta} \quad (4.8)$$

$$= \int \rho_{x1}(x) \rho_{x2}(x) dx \quad (4.9)$$

$$= \Omega_x(\hat{\rho}_{x1}, \hat{\rho}_{x2}) \quad (4.10)$$

For convenience, define $\Sigma_{x,y}$ to be the characteristic widths of $R_{x,y}(\delta)$, given by:

$$\Sigma_{x,y} = \frac{1}{\sqrt{2\pi}} \frac{\int R_{x,y}(\delta) d\delta}{R_{x,y}(0)}. \quad (4.11)$$

For Gaussian beams, $\Sigma_{x,y}$ correspond to the Gaussian width of $R_{x,y}(\delta)$. Finally, the luminosity is given by

$$\mathcal{L} = \frac{f_r n_1 n_2}{2\pi \Sigma_x \Sigma_y}. \quad (4.12)$$

Equating this with the luminosity defined in equation 4.3, the visible cross section for a given detector and algorithm is given by

$$\sigma_{\text{vis}} = \mu_{\text{vis}}^{\text{MAX}} \frac{2\pi \Sigma_x \Sigma_y}{n_1 n_2}, \quad (4.13)$$

where $\mu_{\text{vis}}^{\text{MAX}}$ is the visible interaction rate per bunch crossing at the maximum of the scan curve, $R(\delta)$. The numbers of particles per bunch, $n_{1,2}$, are measured by the LHC Bunch Current Normalization Working Group using bunch current transformers (BCTs) [6–8].

2011 Luminosity Calibration

As an example, the 2011 pp calibration is derived from two pairs of scans in the x - and y -directions, performed during the same LHC fill on 15 May 2011 [2]. The beams had 14 colliding bunch pairs, $\sim 0.8 \times 10^{11}$ protons per bunch, $\beta^* = 1.5$ m, and a crossing angle of $\alpha = 240 \mu\text{rad}$. The resulting transverse beam size was approximately $\sigma_x \approx \sigma_y \approx 40 \mu\text{m}$, and the peak average number of interactions per cross with head-on collisions was $\mu \approx 2.3$. The scan was performed in 25 equal steps over a displacement range of $\delta = \pm 233 \mu\text{m}$.

An example scan curve showing $\mu_{\text{vis}}^{\text{sp}} \equiv \mu_{\text{vis}}/(n_1 n_2)$ as a function of transverse beam separation for the BCMV_OR algorithm is shown in figure 4.2. The vdM scan curve is fitted with a Gaussian plus a constant, which is used as $R_{x,y}(\delta)$ to calculate $\Sigma_{x,y}$ in equation 4.11. $\mu_{\text{vis}}^{\text{MAX}}$ is determined from the peak of the fitted function. The measured σ_{vis} values for both scans and all 14 colliding bunch pairs are shown in figure 4.3. The luminosity-weighted mean σ_{vis} is taken as the central value, while the scatter of the 28 measurements, which is not consistent

with statistical variation, is taken as a systematic uncertainty on the reproducibility of the measurement.

The visible cross sections for several algorithms using during 2011 are shown in table 4.1, along with the efficiency assuming a total inelastic cross section of $\sigma_{\text{inel}} = (71.34 \pm 0.90) \text{ mb}$ [9].

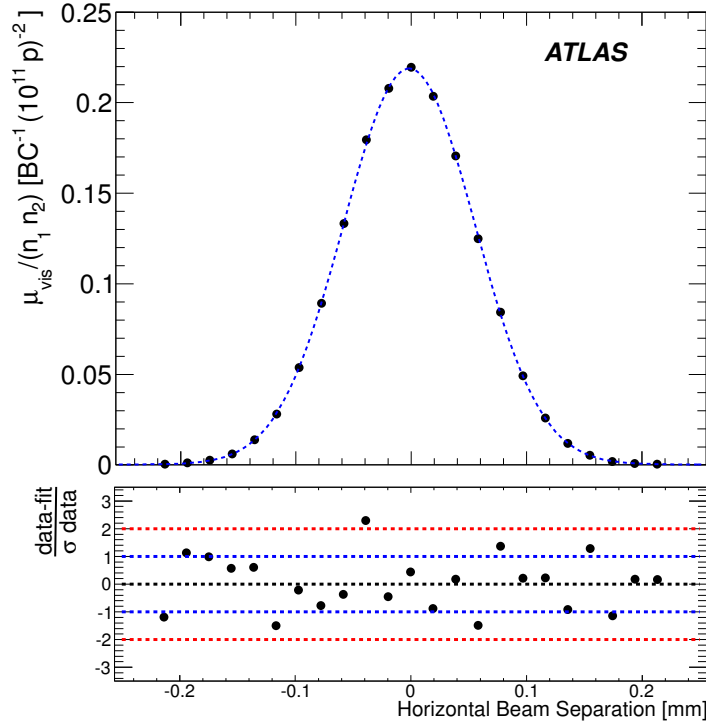


Figure 4.2: An example of a scan curve from the van der Meer scans on 15 May 2011, showing the specific visible interaction rate $\mu_{\text{vis}}^{\text{sp}} \equiv \mu_{\text{vis}}/(n_1 n_2)$ versus transverse beam separation in the x direction for a single scan and BCID. The data are fitted with Gaussian plus constant. The bottom plot shows the residual deviation of the data from the fit, divided by the uncertainty on the data.

4.5 Systematic Uncertainties

The systematic uncertainty on the 2011 and 2012 luminosity measurements are 1.8% and 2.8%³, respectively. No single source of uncertainty dominates the total; rather, the uncertainty is due to many sources, each contributing less than 1%. The sources of uncertainty on the 2011 luminosity measurement are shown in table 4.2, divided into uncertainties on the

³Preliminary uncertainty. The final uncertainty is expected to be below 2%.

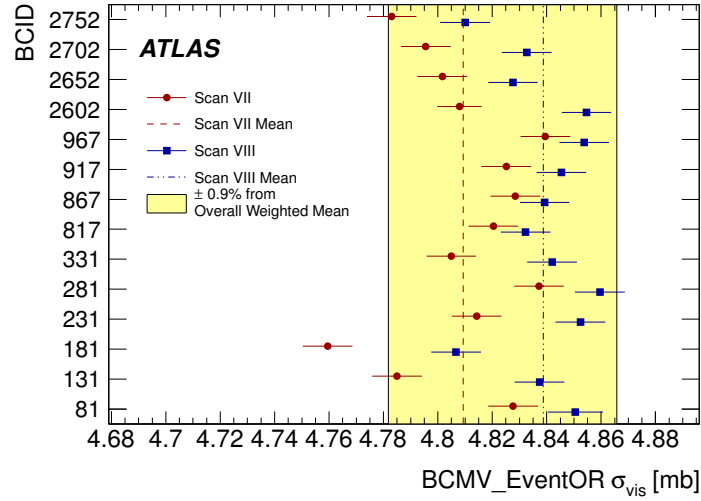


Figure 4.3: Measured σ_{vis} values from the vdM scans performed in May 2011. The error bars represent statistical uncertainties only. The vertical dashed lines indicate the weighted average over BCIDs from the two sets of scans. The yellow band shows a variation of $\pm 0.9\%$ from the total weighted average, equal to the systematic uncertainty due to the observed BCID-to-BCID and scan-to-scan variations.

Algorithm	σ_{vis} (2011)	$\frac{\sigma_{\text{vis}}}{\sigma_{\text{inel}}}$
BCM_VOR	4.82 ± 0.07	0.068
BCM_HOR	4.78 ± 0.07	0.067
BCM_VAND	0.142 ± 0.002	0.002
BCM_HAND	0.140 ± 0.002	0.002
LUCID_OR	43.3 ± 0.7	0.607
LUCID_AND	13.7 ± 0.2	0.192

Table 4.1: Visible cross sections for pp luminosity measurement algorithms used in 2011. The corresponding efficiency of detecting an inelastic pp collision is also shown for $\sigma_{\text{inel}} = 71.34 \text{ mb}$.

visible cross section measurement during vdM scans and uncertainties on the measurement performed over the course of data taking.

The combined uncertainty on the visible cross sections due to the vdM calibration procedure is 1.5%. The largest source of uncertainty is due to emittance growth and non-reproducibility, reflected in the scatter between BCIDs and between scans in figure 4.3. Other significant sources, each roughly 0.5%, include beam-beam effects, where the two colliding beams deflect each other away from the nominal transverse separation; transverse correlations which violate the assumption that the transverse particle densities factorize as $\rho(x, y) = \rho_x(x)\rho_y(y)$; pileup dependence; and the measurement of the number of protons per bunch, $n_{1,2}$.

Uncertainties on the luminosity measurement over the 2011 data-taking period total 0.9%. These uncertainties are dominated by variations in the detector calibrations during 2011, quantified using relative comparisons between algorithms across the entire year, and pileup dependence, quantified using relative comparisons between algorithms at different pileup values. The relative comparisons are shown in figure 4.4.

Source	Uncertainty	
Bunch population product ($n_1 n_2$)	0.5%	} vdM calibration subtotal=1.5% Uncertainties from a single measurement of σ_{vis}
Beam centering	0.10%	
Beam position jitter	0.30%	
Emittance growth/non-reproducibility	0.67%	
Bunch-to-bunch σ_{vis} consistency	0.55%	
Fit model	0.28%	
Background subtraction	0.31%	
Specific luminosity	0.29%	
Length scale calibration	0.30%	
Absolute ID length scale	0.30%	
Beam-beam effects	0.50%	} \mathcal{L} measurement subtotal=0.9% Uncertainties evaluated from all 2011 physics runs
Transverse correlations	0.50%	
Pileup dependence	0.50%	
Afterglow correction	0.2%	
BCM Stability	0.2%	
Long-term consistency	0.7%	
Pileup dependence	0.5%	
Total	1.8%	

Table 4.2: Systematic uncertainties on the integrated luminosity measured in 2011 using the BCM_VOR algorithm. The uncertainties are separated into uncertainties on the visible cross section (1.5%) and measurement uncertainties over the year (0.9%).

4.6 Vertex-Based Luminosity Measurement

Primary vertices are points consistent with being the origin of a set of tracks reconstructed by the inner detector, nominally due to inelastic pp interactions. The reconstruction of tracks and vertices is described in section 5.1. Vertex counting [10] is an appealing luminosity measurement technique for a number of reasons. The backgrounds are very low, and can be

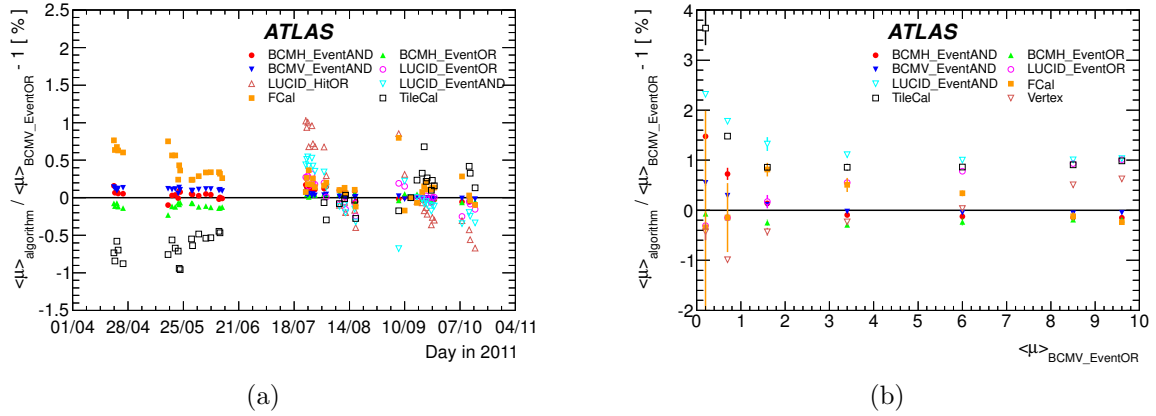


Figure 4.4: Left: Comparison of luminosities measured by different algorithms as a function of time in 2011. Right: Comparison of luminosities measured by different algorithms as a function of the average number of interactions per bunch cross, μ , as measured by BCM_VOR. The data were taken during a single run by separating the beams in the transverse direction, similar to a van der Meer scan.

controlled by requiring a minimum number of tracks per vertex, chosen here to be five tracks with $p_T > 400$ MeV. Further, the vertex reconstruction efficiency is expected to be stable throughout the data taking period. However, the technique has two significant drawbacks. First, the data is collected through the standard ATLAS data acquisition system, limiting the event rate during normal physics runs to $\mathcal{O}(100 \text{ Hz})$. Depending on the trigger used, a correction for the trigger deadtime may also be necessary. Second, the efficiency of the vertex reconstruction algorithm is significantly nonlinear with pileup, with the efficiency decreasing by $\sim 30\%$ between pileup values of $\mu = 1$ and $\mu = 30$.

Vertex Counting Method

The data for the inner detector-based luminosity measurements are collected through the standard ATLAS data acquisition system. Events are collected with either a random trigger or a trigger requiring hits in the minimum bias trigger scintillators (MBTS), two discs of scintillators mounted on the inner surfaces of the LAr end-cap cryostats ($2.12 < |\eta| < 3.85$). The random trigger records a fraction of all bunch crossings in a specific set of BCIDs, enabling an unbiased measurement of μ_{vis} at the cost of lower statistics. The statistics collected worsen at low pileup values, where a large fraction of the triggered events do not contain a collision; hence, the random trigger is used mostly at high pileup. The MBTS trigger requires hits MBTS, usually at least two. The trigger inefficiency, prescale, and deadtime must be taken into account. For vertices with at least five tracks, the inefficiency is negligible. Both triggers can select a specific set of BCIDs, which is essential for special runs where a bunch-by-bunch measurement is necessary, e.g. the vdM scans.

Vertices are reconstructed with two settings: the default reconstruction settings based on tracks with $p_T > 400$ MeV, and tighter settings (“VtxLumi”) based on tracks with $p_T > 900$ MeV with stricter requirements on the track quality. The tighter settings were introduced in 2012 to reduce the computational requirements associated with collecting $\mathcal{O}(100 \text{ Hz})$ of inner detector data over the entire year. The studies described below are based on the 2011 data, where the vertex-based luminosity measurement is only performed on special runs, and use the default reconstruction settings.

The single-bunch instantaneous luminosity is calculated as follows. For the random trigger, the visible interaction rate is $\mu_{\text{vis}} = \frac{N_{\text{vtx}}}{N_{\text{evt}}}$, where N_{vtx} is the number of vertices recorded in N_{evt} triggered events. For the MBTS trigger, $\mu_{\text{vis}} = \frac{N_{\text{vtx}}}{f_r t}$, where N_{vtx} is the number of vertices recorded after correcting for the prescale and deadtime, $f_r = 11\,245.5 \text{ Hz}$ is the LHC revolution frequency, and t is the duration of the measurement. μ_{vis} is then corrected for pileup effects, described below in section 4.6, and finally the luminosity is given by equation 4.3.

Pileup Effects

The vertex reconstruction efficiency is strongly affected by three pileup-related phenomena:

- Vertex masking: a pp interaction fails to be reconstructed as a vertex because some or all of its tracks are used by an earlier vertex in the iterative reconstruction algorithm. This is the dominant pileup effect, which causes a large drop in the reconstruction efficiency at high pileup.
- Fake vertices: a vertex passes the cut on the minimum number of tracks due to acquiring tracks from another nearby pp interaction. This is a subdominant but significant effect, which causes a small increase in the reconstruction efficiency at high pileup.
- Split vertices: a single interaction is reconstructed as two separate vertices. This is a significant effect when considering vertices with two or more tracks, but is negligible for vertices with at least five tracks.

Corrections are derived for vertex masking and fake vertices. The fake vertex correction is derived using truth matching in minimum bias Monte Carlo simulation. The simulation sample was generated using PYTHIA 8, with tune A2M [11, 12]. For a given cut on the minimum number of tracks per vertex, m , a reconstructed vertex is labelled as fake if less than m of its tracks are matched to charged particles originating from the same generated pp interaction. The average number of reconstructed vertices labelled as fake by Monte Carlo truth matching is shown as a function of pileup in figure 4.6. The fake fractions show a significant dependence on μ and on the minimum number of tracks per vertex.

A correction is derived for vertex masking using the distribution of longitudinal distances, Δz , between pairs of vertices in the same event. In the absence of masking, if the interaction region has a Gaussian longitudinal profile with width σ_z , then the Δz distribution would

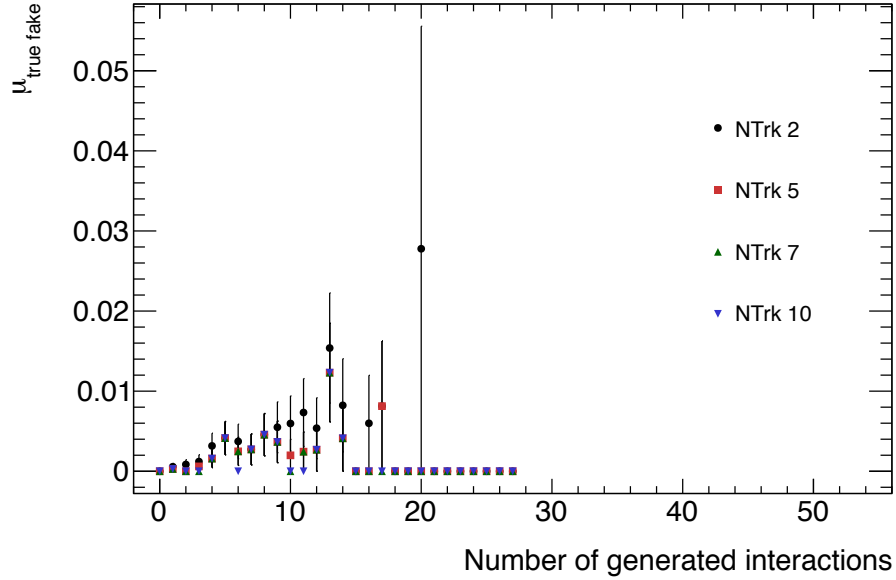


Figure 4.5: Average number of reconstructed vertices without a matched truth interaction, as a function of number of generated interactions per event. The contribution is below 0.1%.

be a Gaussian with width $\sigma_z \times \sqrt{2}$. Masking manifests as an absence of reconstructed pairs near $\Delta z = 0$, as shown in figure 4.7.

The correction is derived in a data-driven way as follows.

1. In a data sample with exactly two interactions per event, the number of masked pairs is equal to the number of masked vertices. Using data taken at low pileup values and selecting events with exactly two reconstructed vertices, we calculate the 2-vertex masking probability $p_{\text{mask}}(\Delta z)$, i.e. the probability that only one of two vertices separated by Δz is reconstructed. This function is assumed to be a universal property of the vertexing algorithm, independent of μ .

Specifically, the expected Δz distribution in the absence of masking, $f_{\text{exp}}(\Delta z)$, is derived by randomly sampling pairs of points from the observed z -distribution of reconstructed vertices. Using $f_{\text{exp}}(\Delta z)$ as a template, the *observed* Δz distribution, $f_{\text{obs}}(\Delta z)$, is fitted in the range $30 \text{ mm} \leq |\Delta z| \leq 300 \text{ mm}$, where vertex masking is negligible. Finally, the masking probability is defined as:

$$p_{\text{mask}}(\Delta z) = \frac{f_{\text{exp}}(\Delta z) - f_{\text{obs}}(\Delta z)}{f_{\text{exp}}(\Delta z)} \quad (4.14)$$

The masking probability functions derived from minimum bias Monte Carlo and for low- μ data are shown in figures 4.8 and 4.9.

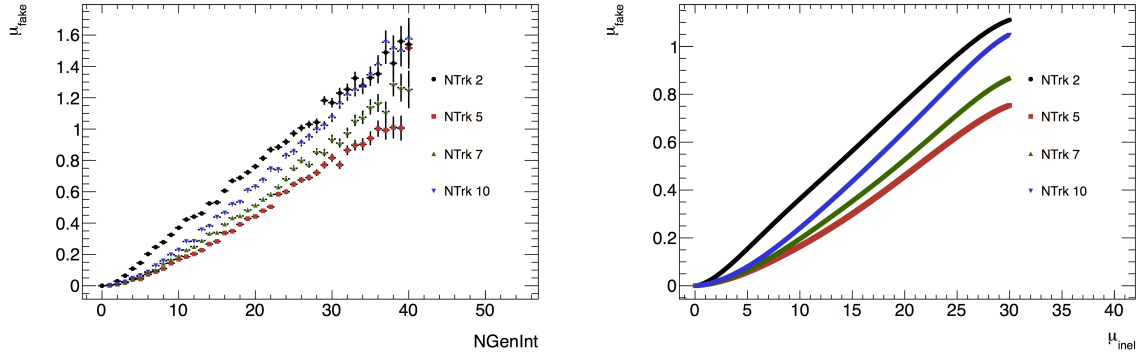
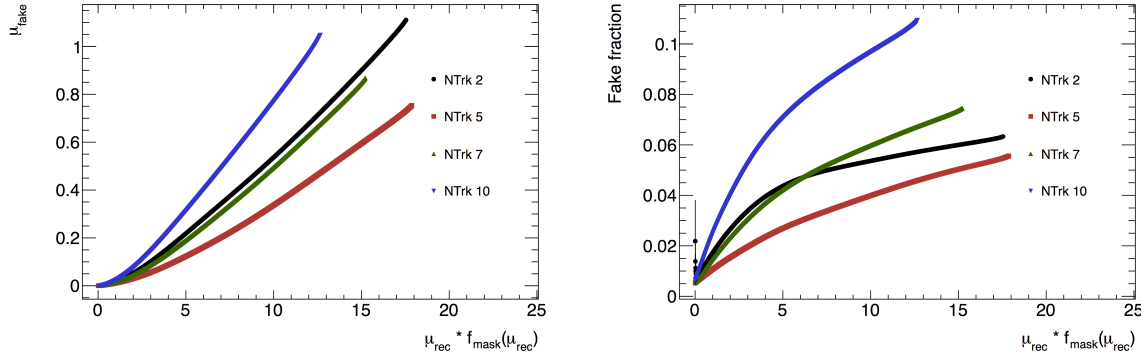
(a) μ_{fake} vs. number of generated interactions per event.(b) μ_{fake} vs. μ_{inel} .(c) μ_{fake} vs. μ_{rec} after masking correction.(d) $\mu_{\text{fake}}/\mu_{\text{rec}}$ vs. μ_{rec} after masking correction.

Figure 4.6: Fraction of reconstructed vertices labelled as fake by Monte Carlo truth matching, as a function of pileup.

2. To derive a correction for a particular data sample at arbitrary μ , an *expected* Δz distribution, $f_{\text{exp}}(\Delta z)$, is again derived by randomly sample pairs of vertices from the observed primary vertex z -distribution. Then, the total probability p_{mask} that given any two tight vertices, only one is reconstructed can be computed:

$$p_{\text{mask}} = \int_{-\infty}^{\infty} p_{\text{mask}}(\Delta z) f_{\text{exp}}(\Delta z) d(\Delta z). \quad (4.15)$$

3. The total masking probability p_{mask} is used to generate a map between the number of reconstructible vertices per event, N_{vis} , and the average number of reconstructed vertices per event, μ_{rec} , as follows. Label the generated vertices v_i , $1 \leq i \leq N_{\text{gen}}$, in the order in which the iterative vertexing algorithm reconstructs the vertices; similarly, let p_i , $1 \leq i \leq N_{\text{vis}}$, be the probability that vertex v_i is reconstructed. Proceeding vertex-by-vertex, the p_i follow a recursion relation:

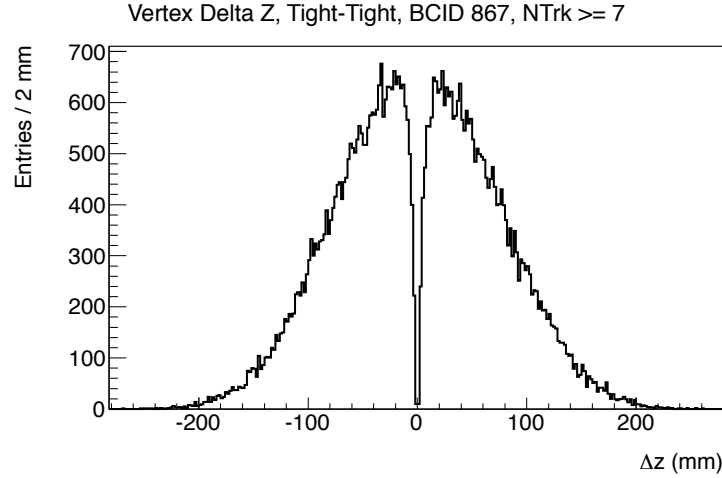


Figure 4.7: Δz distribution between pairs of vertices in the same event, with data from the May Van der Meer scan (ATLAS run 182013).

$$p_1 = 1 \quad (4.16)$$

$$p_2 = p_1 \times (1 - p_{\text{mask}}) \quad (4.17)$$

$$\dots \quad (4.18)$$

$$p_k = \prod_{i=1}^{k-1} (p_i \times (1 - p_{\text{mask}}) + (1 - p_i) \times 1) \quad (4.19)$$

$$= \prod_{i=1}^{k-1} (1 - p_i p_{\text{mask}}) \quad (4.20)$$

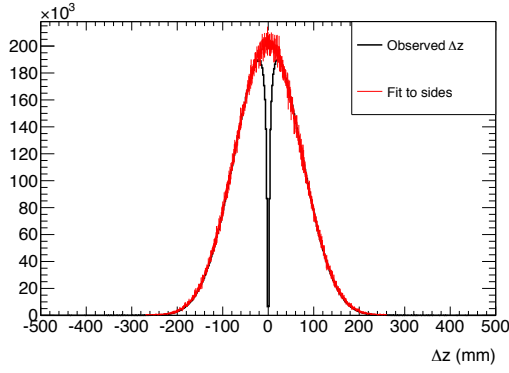
$$= p_{n-1} \times (1 - p_{n-1} p_{\text{mask}}) \quad (4.21)$$

The average number of reconstructed vertices is then:

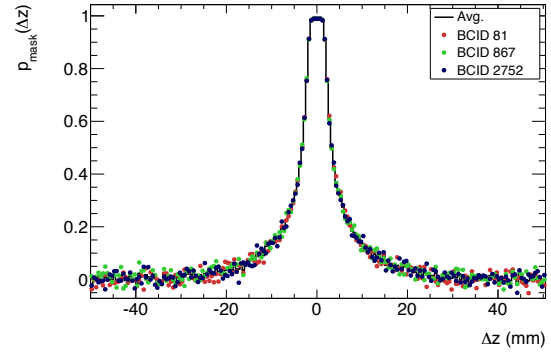
$$\langle N_{\text{rec}} \rangle = \sum_{i=1}^{N_{\text{vis}}} p_i. \quad (4.22)$$

4. Finally, a map is computed between the average number of reconstructible vertices, μ_{vis} , and the average number of reconstructed vertices, $\mu_{\text{rec}}(\mu_{\text{vis}})$, by convoluting $\mu_{\text{rec}}(N_{\text{vis}})$ with a Poisson distribution:

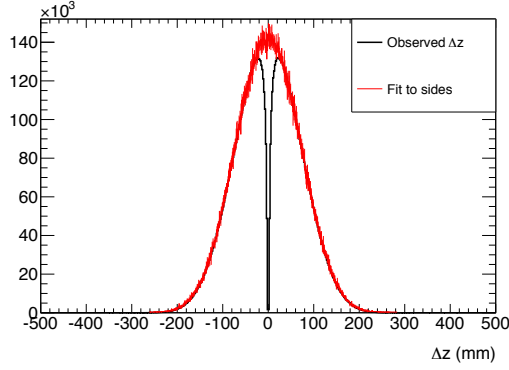
$$\langle \mu_{\text{rec}} \rangle(\mu_{\text{vis}}) = \sum_{N_{\text{vis}}=0}^{\infty} P(N_{\text{vis}}; \mu_{\text{vis}}) \mu_{\text{rec}}(N_{\text{vis}}). \quad (4.23)$$



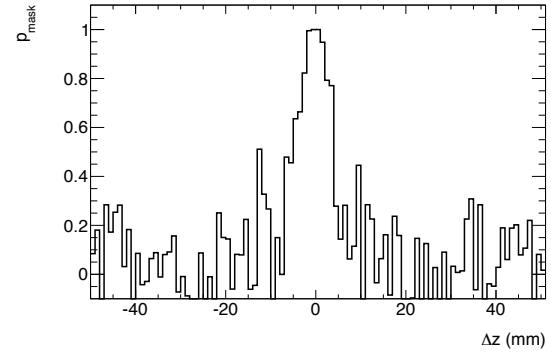
(a) Δz distribution and template fit, NTrk5, BCID 81



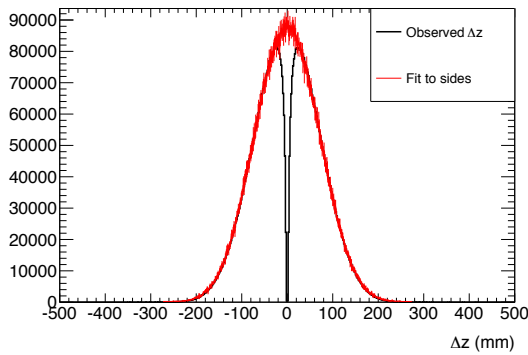
(b) $p_{\text{mask}}(\Delta z)$, NTrk5



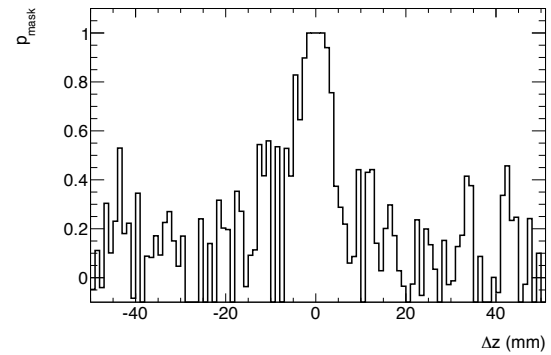
(c) Δz distribution and template fit, NTrk7, BCID 81



(d) $p_{\text{mask}}(\Delta z)$, NTrk7



(e) Δz distribution and template fit, NTrk10, BCID 81



(f) $p_{\text{mask}}(\Delta z)$, NTrk10

Figure 4.8: Calibration of the masking correction method on data, using run 182013. Left: Δz distributions and template fits using expected Δz distributions in the range $30 \text{ mm} \leq \Delta z \leq 300 \text{ mm}$. Right: pairwise vertex masking probability as a function of the longitudinal distance Δz between the vertices.

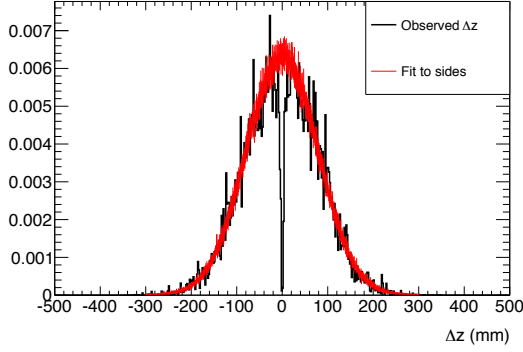
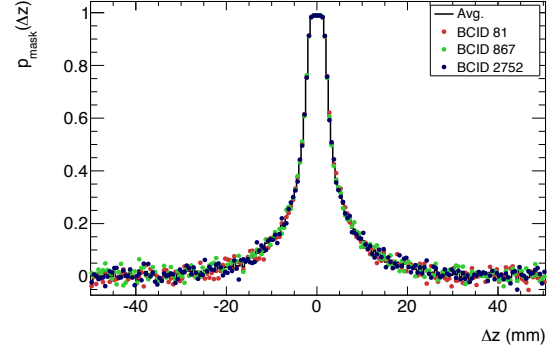
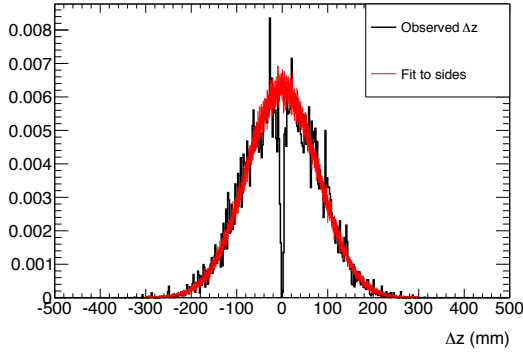
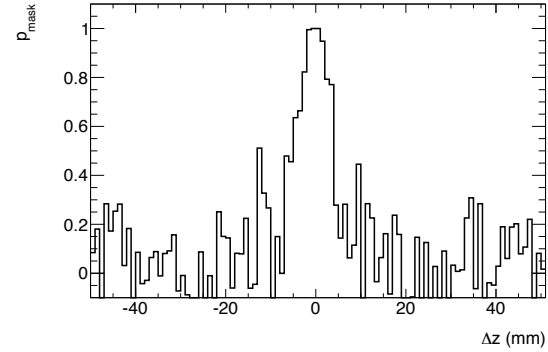
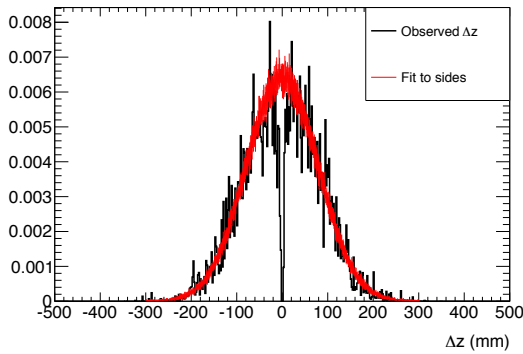
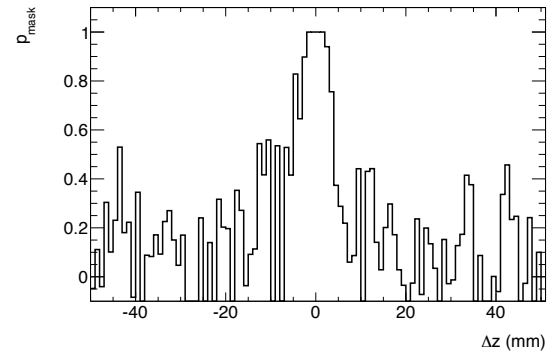
(a) Δz distribution and template fit, NTrk5(b) $p_{\text{mask}}(\Delta z)$, NTrk5(c) Δz distribution and template fit, NTrk7(d) $p_{\text{mask}}(\Delta z)$, NTrk7(e) Δz distribution and template fit, NTrk10(f) $p_{\text{mask}}(\Delta z)$, NTrk10

Figure 4.9: Calibration of the masking correction method on simulation, using 8 TeV minimum bias Monte Carlo (pythia 8, tune A2M). Left: Δz distributions and template fits using expected Δz distributions in the range $30 \text{ mm} \leq \Delta z \leq 300 \text{ mm}$. Right: pairwise vertex masking probability as a function of the longitudinal distance Δz between the vertices.

Vertex-Based Luminosity Measurements

Due to the low event rate available during physics runs, vertex counting was used to measure luminosity only in three special runs during 2011, where inner detector data was recorded by a special high-rate data stream. The data stream reads out events at $\mathcal{O}(10\text{ kHz})$, recording only the inner detector from a small number of bunch crossings, typically less than four. The three runs are the vdM calibration run in May 2011, the pileup scan in September 2011 shown in figure 4.4b, and a high- β^* run with a single bunch used to measure the total pp cross section using the ALFA detector.

Van der Meer Scan

An example scan curve from the May 2011 vdM scan is shown in figure 4.10. The trigger used to collect the data required hits in the minimum bias trigger scintillators (MBTS), and selected 3 of the 14 colliding bunch pairs. The peak interaction rate during the scan was $\mu \sim 1.97$. The data are corrected for vertex masking and fakes, with the correction factor reaching up to 3% at the peak of the scan curves. Following the protocol described in section 4.4, the visible cross section is determined to be $(38.50 \pm 0.12)\text{ mb}$, where the uncertainty reflects the RMS spread between the three bunch crossings and the two scans.

Pileup Scan

The September 2011 pileup scan is used to derive systematic uncertainties due to the non-linear response of algorithms with respect to the number of interactions per bunch crossing. The scan was performed at the end of a physics run, displacing the beams in the transverse direction to obtain a sample of data at over a pileup range of $0.02 \lesssim \mu \lesssim 10$ with otherwise identical conditions. The data was triggered by a random trigger selecting events from two bunch crossings, BCIDs 200 and 999. The data are corrected for vertex masking and fakes, with the correction reaching up to 10% as shown in figure 4.11 with respect to BCM_VOR. A comparison of the luminosity measurements between vertex counting and BCM_VOR, shown in figure 4.12, exhibits a slope of about 0.1% per unit of μ .

ALFA Run

Finally, vertex counting provides a reliable luminosity measurement for the 2011 ALFA run, a special run used for a measurement of the total pp cross section [13]. The beams contained a single colliding bunch pair with $\beta^* = 90\text{ m}$ and $\mu \sim 0.03$, in order to measure the scattering angle of elastic pp collisions. A special luminosity analysis is required to address the very low instantaneous luminosity of $\mathcal{L} \sim 5 \times 10^{27}\text{ cm}^{-2}\text{ s}^{-1}$, about six orders of magnitude lower than a typical physics fill. The calorimeter methods are unusable due to a

lack of sensitivity. For BCM and LUCID, the backgrounds at low instantaneous luminosity have a different composition: afterglow is negligible with a single colliding bunch, but beam-gas interactions can be significant, resulting in an extra 0.2% systematic uncertainty. The low-pileup conditions are ideal for vertex counting, eliminating the need to perform pileup corrections. The requirement of at least five tracks with $p_T > 400$ MeV per vertex suppresses the beam-gas backgrounds. The data were recorded by a random trigger at approximately 1 kHz.

A comparison of luminosity measurements from BCM, LUCID, and vertex counting is shown in figure 4.13. To be consistent with the primary pp luminosity measurement, the central value is taken from BCM_VOR; vertex counting shows agreement with this value to within 0.5%.

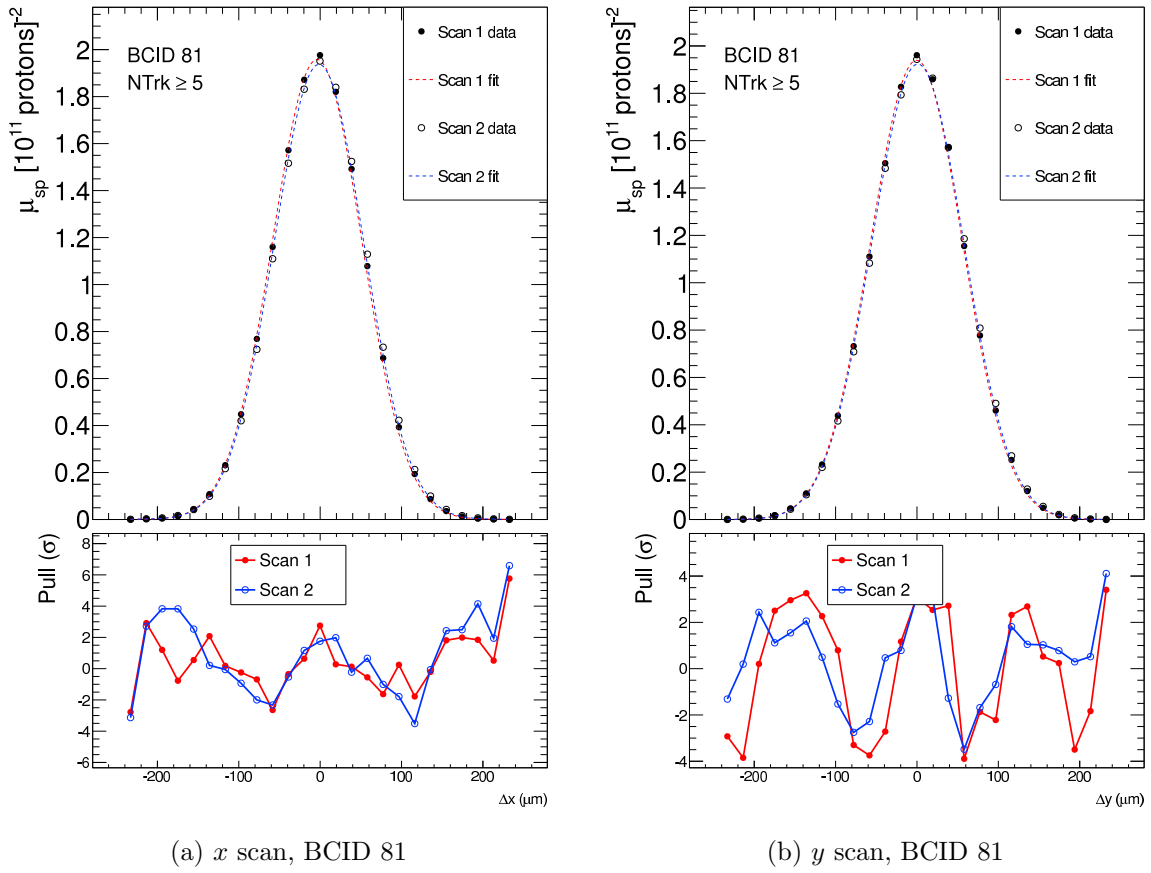
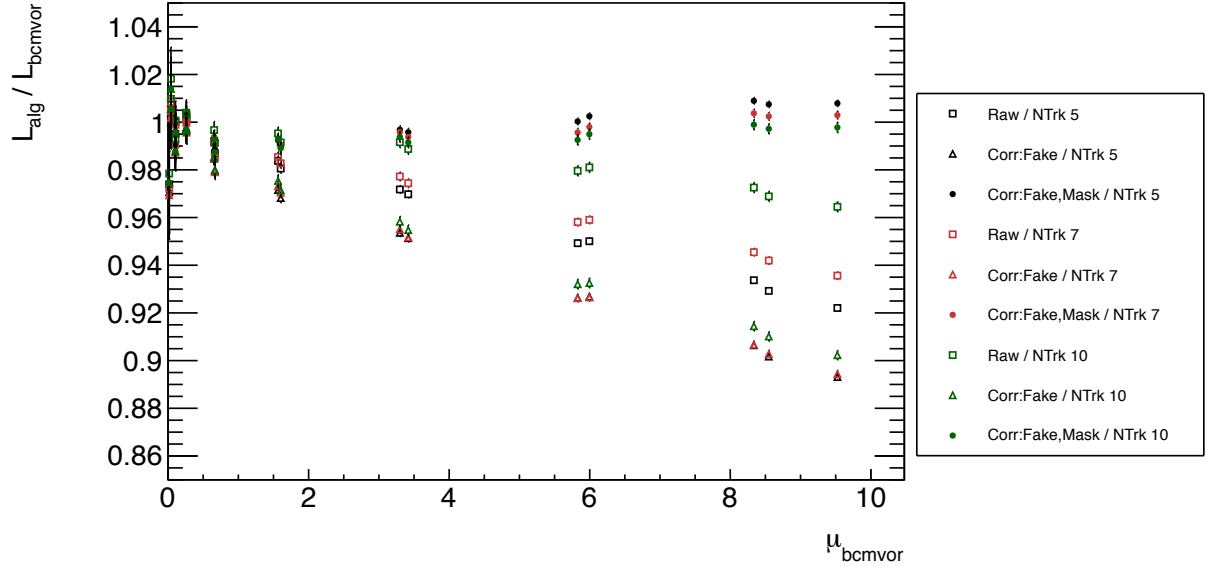
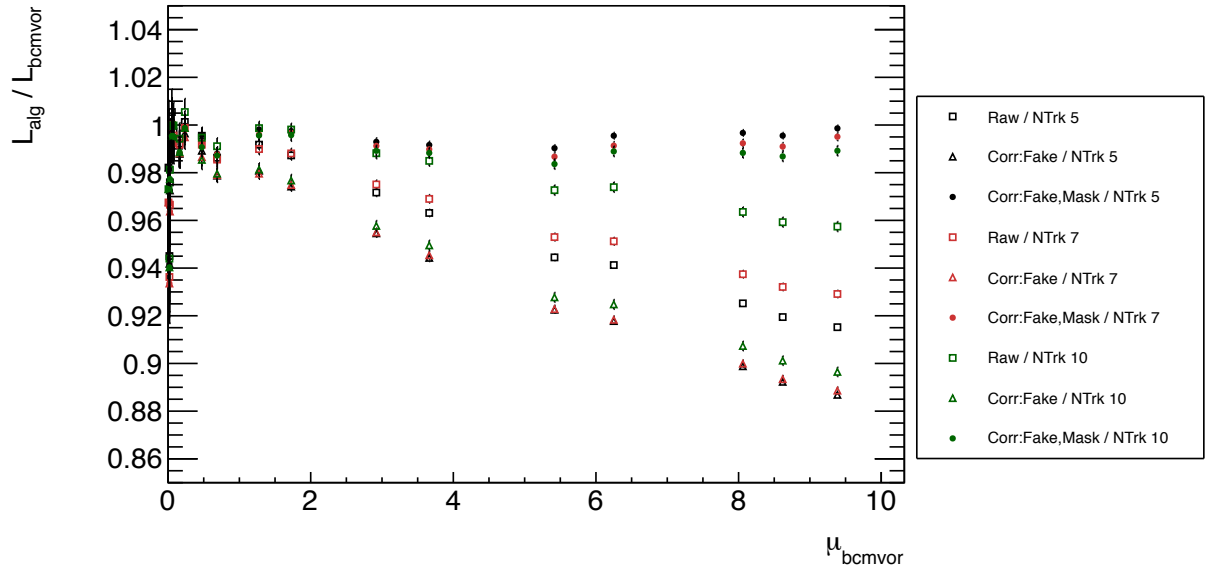


Figure 4.10: $\mu_{\text{vis}}^{(sp)}$ vs. beam separation, with single gaussian plus constant fits, and pulls.



(a) BCID 200



(b) BCID 999

Figure 4.11: Ratio of luminosity values from vertexing and BCM_VOR, shown with each successive pileup correction applied. Fakes are subtracted first, and masking is corrected second.

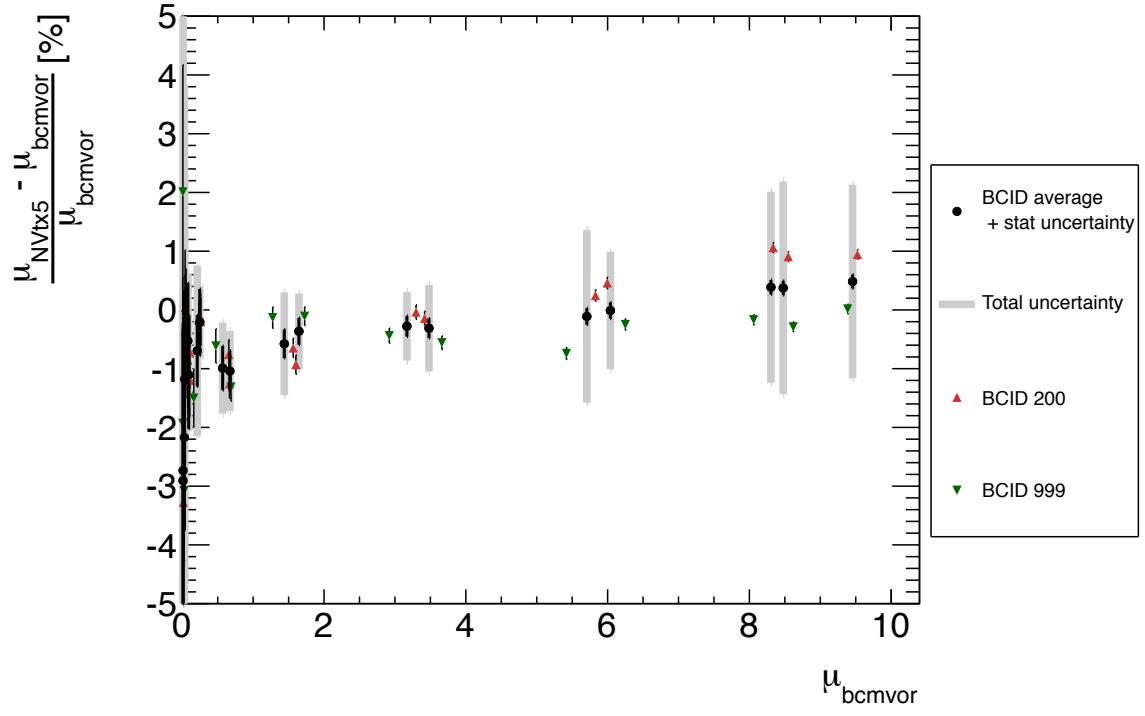


Figure 4.12: Percent difference between luminosities measured by vertex counting and BCM_VOR. The central values are taken to be the average between BCIDs 200 and 999.

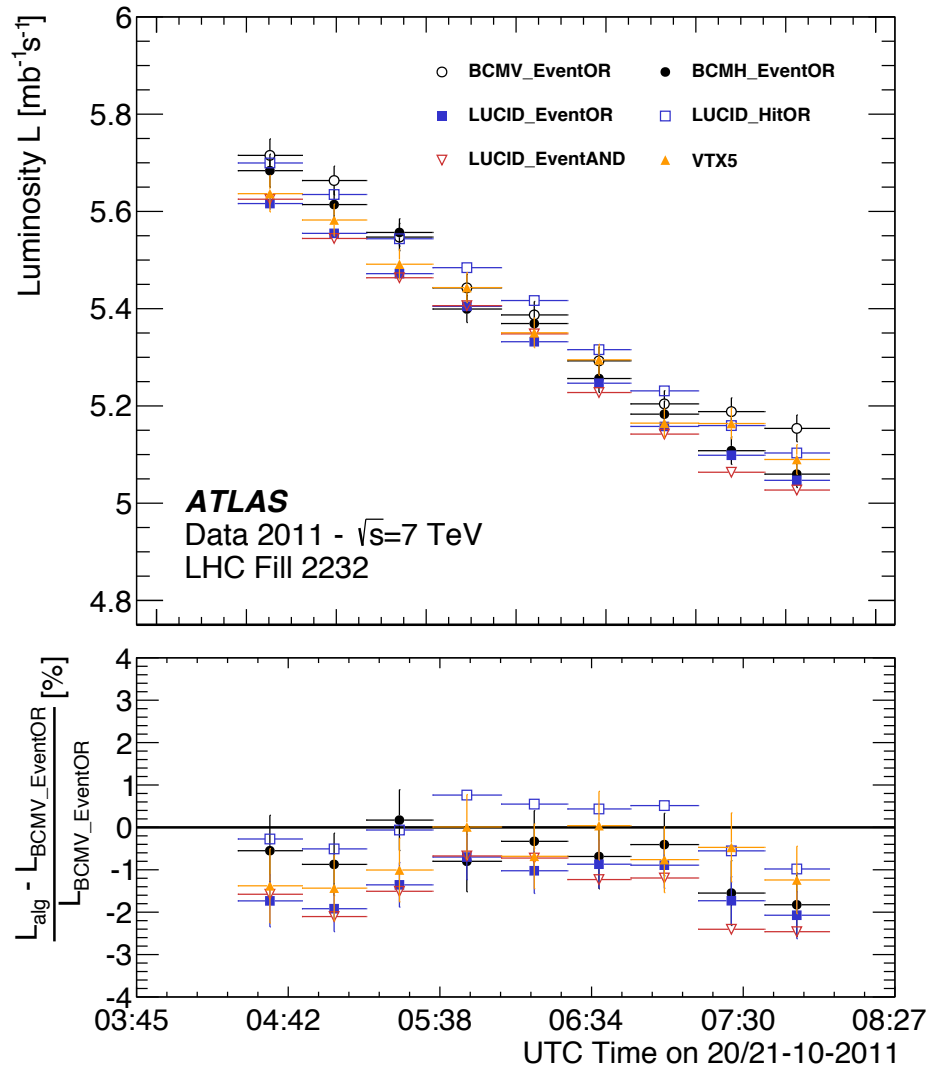


Figure 4.13: Luminosities measured by BCM, LUCID, and vertex counting during the $\beta^* = 90$ m ALFA run in October 2011.

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