ZEUS Note 95–138

Determination of the ZEUS Luminosity in 1994

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Abstract

The note describes a procedure of the luminosity measurement in ZEUS in 1994 with the detailed discussion of its systematic errors.

1 Introduction

Procedure of the luminosity measurement in ZEUS in 1994 was similar to that in 1993 therefore in this note we focus mainly on the new features of the luminosity measurement and for more details we refer to [1].

Following changes in the experimental set-up of the luminosity monitor were done in 1993/94 winter shutdown to improve linearity and resolution of the photon energy measurement:

- installation of a 12.4 m long (with changing diameter from 100 to 150 mm) vacuum chamber in front of the photon detector to minimize amount of dead-material;
- shifting of the carbon filters towards the photon calorimeter to decrease shower side leakages (however, at the expense of the efficiency of synchrotron radiation suppression);
- modification of the photon calorimeter: making a first scintillator plate four times thicker than the other 2.6 mm plates to correct (in average) for energy losses in the carbon filters;
- the photomultiplier tubes were changed from XP2011 to XP2081 which had weaker gain sensitivity on large anode currents (see [2]);
- installation of the new LED pulser flashing in empty HERA buckets at the rate of about 3 kHz (simultaneously with the ZEUS data taking and luminosity measurement).

Additionally, an on-line procedure of the luminosity calculation has been significantly improved by including corrections for non-nominal beam tilts, pedestals and for event pileup effects, and by optimizing the trigger cuts selecting so-called 'luminosity events' [3].

2 Running Condition

2.1 HERA Performance

In the 1994 running period HERA provided luminosity for experiments from the end of May till the end of October. The bunch structure of the beams was: 153 colliding bunches, 15 electron

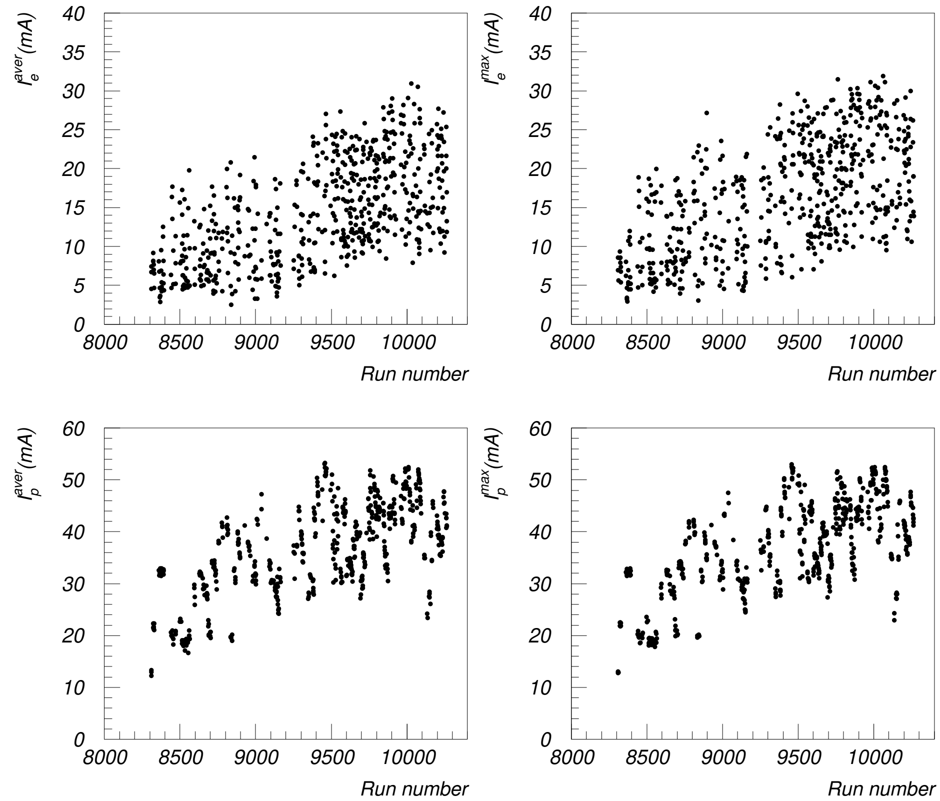

Figure 1: HERA performance: Average and maximum beam currents as a function of the ZEUS run number.

and 17 proton pilot bunches. Colliding bunches were stored in 9-bunch trains. Between 18 and 29 July 1994 the HERA switched from electron to positron running due to persisting electron beam life-time problems.

The most important parameters which characterize the HERA performance in 1994 are shown in Figs. 1,2,3,4 as a function of the ZEUS run number. A progress achieved by HERA during the running period can be clearly seen. Both the specific and instantaneous luminosity were steadily improving. The typical beam currents at the beginning of collisions increased from 5 and 10 mA in June up to 30 and 50 mA in October 1994 for electron/positron and proton beams, respectively. The maximum instantaneous luminosity reached $\approx 5 \times 10^{30} cm^{-2}s^{-1}$, i.e. 30% of the design value. The observed maximum specific luminosity, $\approx 6 \times 10^{29} cm^{-2}s^{-1}mA^{-2}$, was higher than design value.

2.2 Luminosity Monitor Operation

As was mentioned the photon calorimeter was modified in the 93/94 winter shutdown to improve linearity and resolution of the energy measurement. In Fig. 5 a cross-section of the modified photon calorimeter is shown. It was found however that an initial filter against synchrotron radiation was too thin (1 X_0 of carbon) and a significant pedestal shift of a few ADC counts due to synchrotron radiation signal was observed (see [4]). Therefore, to suppress this background the filter thickness was increased. In Tab. 1 three filter configurations used in 1994 are described[1]. The gain stability was much better than in 1993 inspite of much higher beam currents and event rates [5]. There were, however, significant pedestal shifts (both due to synchrotron radiation signal and due to radiation damage of the front-end electronics) and two abrupt jumps which were not really understood.

[1]For the last configuration a 6 mm thick lead plate ($\equiv 1\ X_0$) was installed at the front plate of the γcal housing (in addition to a 5.7 mm lead plate installed directly at the photon calorimeter, see Fig. 5).

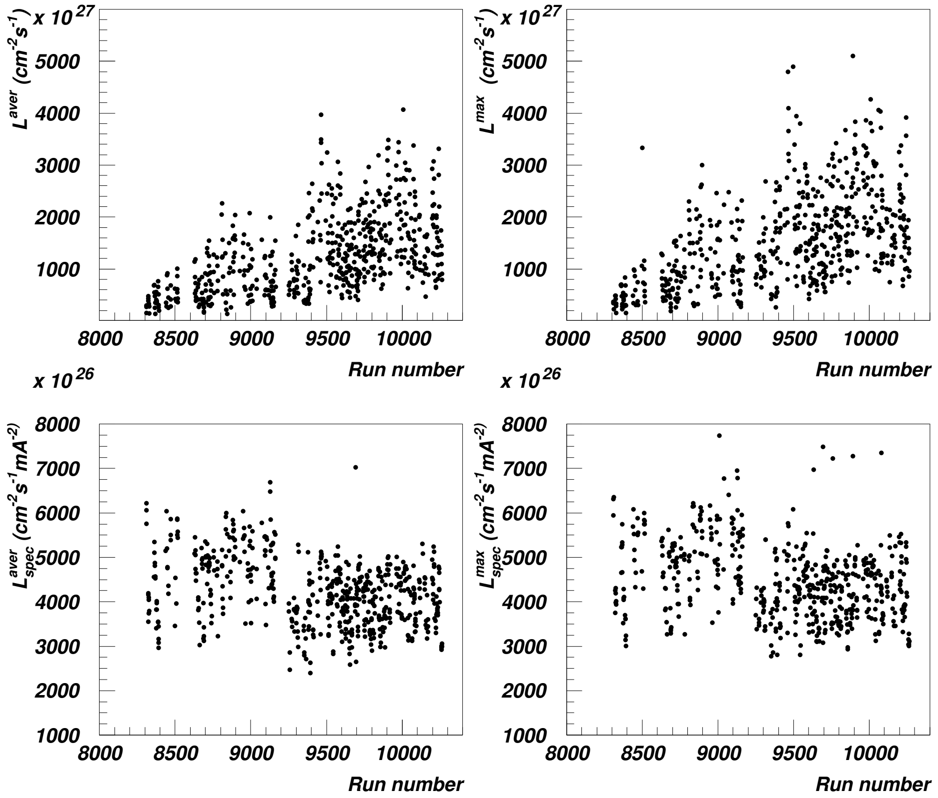

Figure 2: HERA performance: Average and maximum instantaneous and specific luminosities as a function of the ZEUS run number.

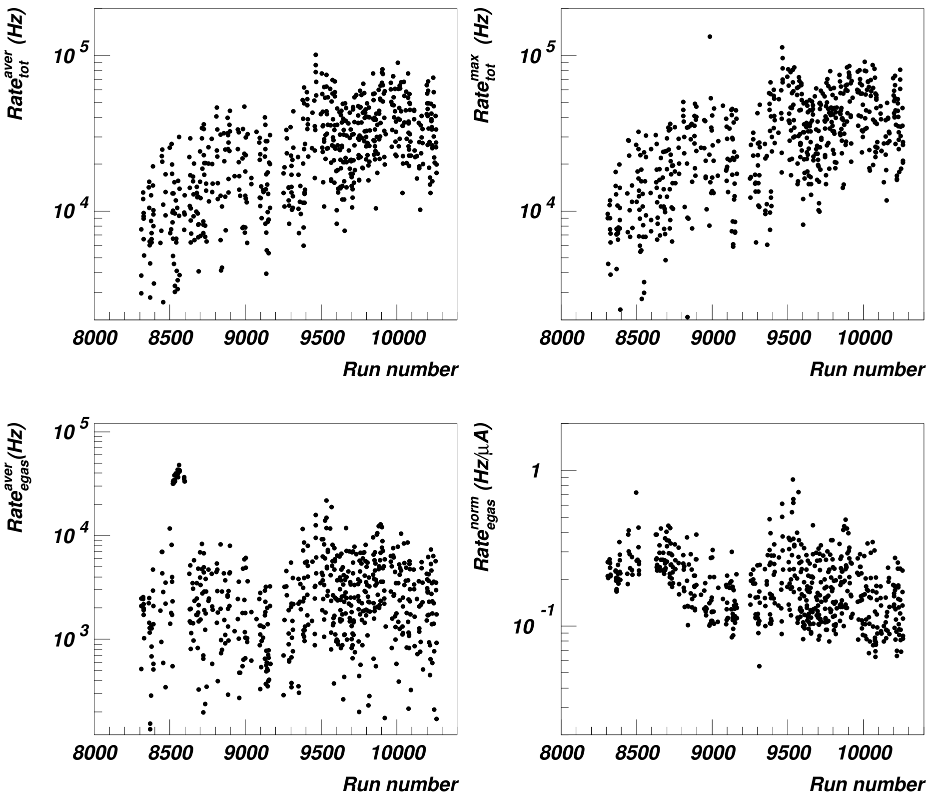

Figure 3: HERA performance: Average and maximum total bremsstrahlung rates, and average $egas$ bremsstrahlung rate for the $16 > E_\gamma > 10$ GeV trigger as a function of the ZEUS run number; the last plot shows history of the $egas$ rate normalized with the current of electron pilot bunches (which is proportional to the rest gas pressure close to the IP).

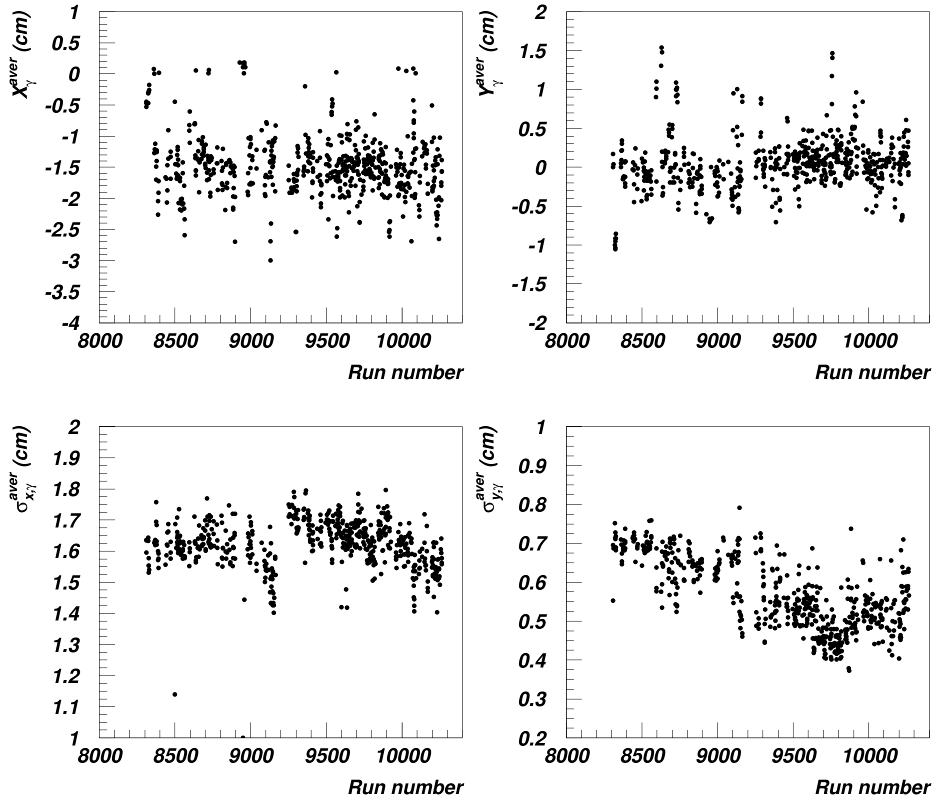

Figure 4: HERA performance: Average positions and widths of the photon beam at γcal as a function of the ZEUS run number.

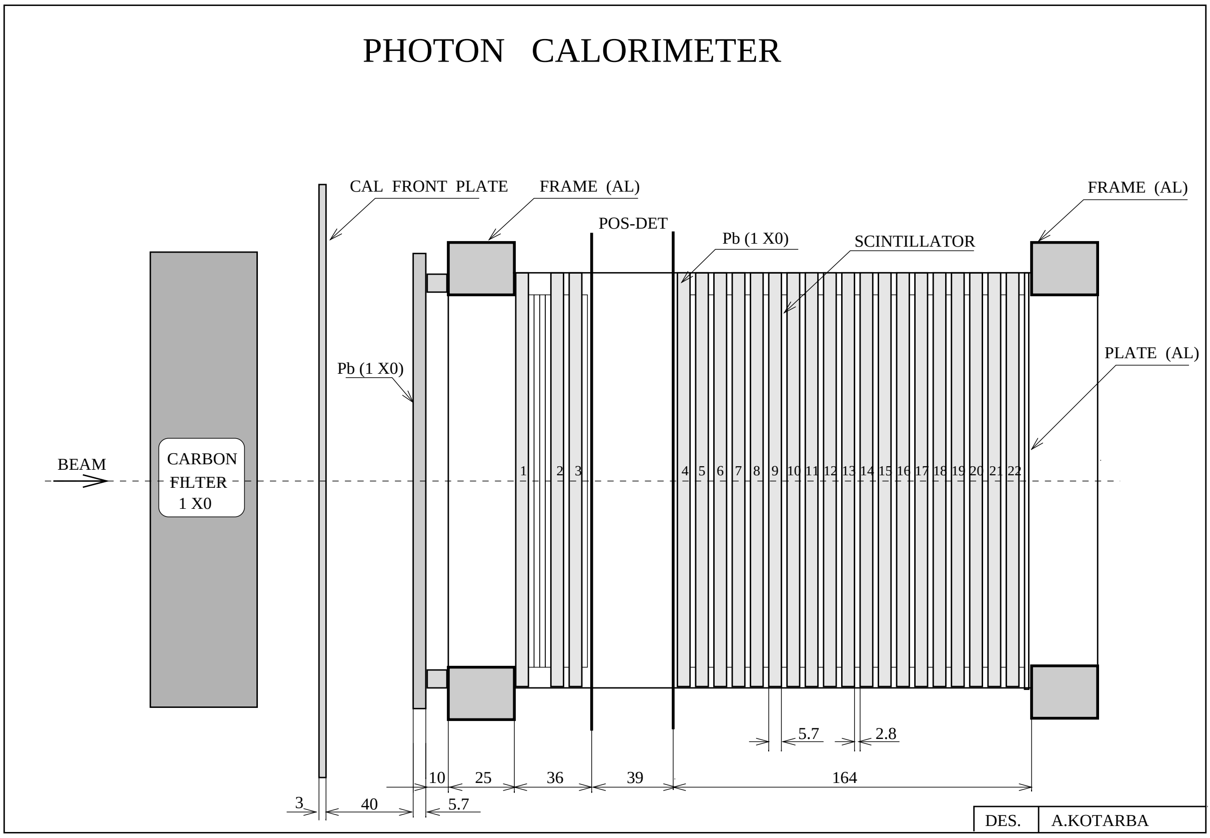

Figure 5: Sketch of the new photon calorimeter design with a thick first scintillator plate ('presampler') and an insertion of a position detector shifted toward a face of the detector.

Table 1: Synchrotron Radiation Filter Configurations in 1994

Time	Run range	Configuration
–24.07	–9180	a) $1X_0$ carbon
24.07–30.08	9181–9600	b) $1X_0$ carbon+$1/2X_0$ lead
31.09–	9601–	c) $1{+}1/2X_0$ carbon+$1X_0$ lead

Table 2: Two experimental corrections (pileup correction corresponds to $3\times10^{30}cm^{-2}s^{-1}$ luminosity and 10% of $egas$ background) and the final MC 'observed' cross-section for three filter configurations and four trigger cuts.

Correction type		Trigger type $ADC_\gamma > 21$	> 42	> 77	$120 > ADC_\gamma > 77$
FADC threshold value		+0.07%	+0.22%	–0.08%	–0.45%
Event pile-up		–2.03%	–0.27%	+0.89%	–0.53%
Final σ_{obs}(mb)	a	125.0	72.89	39.03	19.22
	b	122.1	71.74	38.67	18.97
	c	117.8	70.37	38.21	18.67

3 Luminosity Determination

3.1 Monte Carlo Simulation

For the simulation of the luminosity detector the fast Monte Carlo simulation described in [6] was used. High statistics MC data samples were produced for 27.52 GeV electron and 820 GeV proton beam energies, all together more than 10^8 ep bremsstrahlung events were generated with photon energies in the range $27.52 > E_\gamma > 0.1$ GeV. Since the cross-section for this energy range is 329 mb, the sample corresponds to an integrated luminosity of about 0.2 nb^{-1}.

Geometrical acceptance of bremsstrahlung photons was simulated using the acceptance contour described in Sec. 4.3 in [1] with a nominal acceptance of 99%. Then, by applying the same cuts (in ADC counts) which were used for counting luminosity events on-line, the number of triggered luminosity events and corresponding 'observed' cross-sections were found.

There were two more corrections applied: 1) correction due to unequal FADC bin widths (see [1]) and; 2) correction due to pileup of more than one bremsstrahlung event in a single beam collision (obtained from the fast MC simulation as described in [6]), assumed to be due to double events only, i.e. the correction was proportional to the event rate.

Both, corrections as well as final cross-sections (without pile-up correction which has to be applied on a run-to-run basis) for three filter configurations and four trigger types are listed in Tab. 2.

3.2 Online Procedure

Online calculations were done using the VME LUMI scalers, bunch current data and on-line data from photon position detector. Up to the run number 8746 the on-line software had wrong constants loaded (for 26.67 GeV electron beam). Since 1.09.1994 (run #>9622) a new algorithm was used with corrections for non-nominal electron beam tilts (nominal tilt was assumed at -0.15 mrad horizontally and 0.0 mrad vertically), pedestals (nominal pedestal was equal 12.0 ADC counts) and for the effects of event pileup [7]. On 26.09.1994 (valid for run # > 9854) the

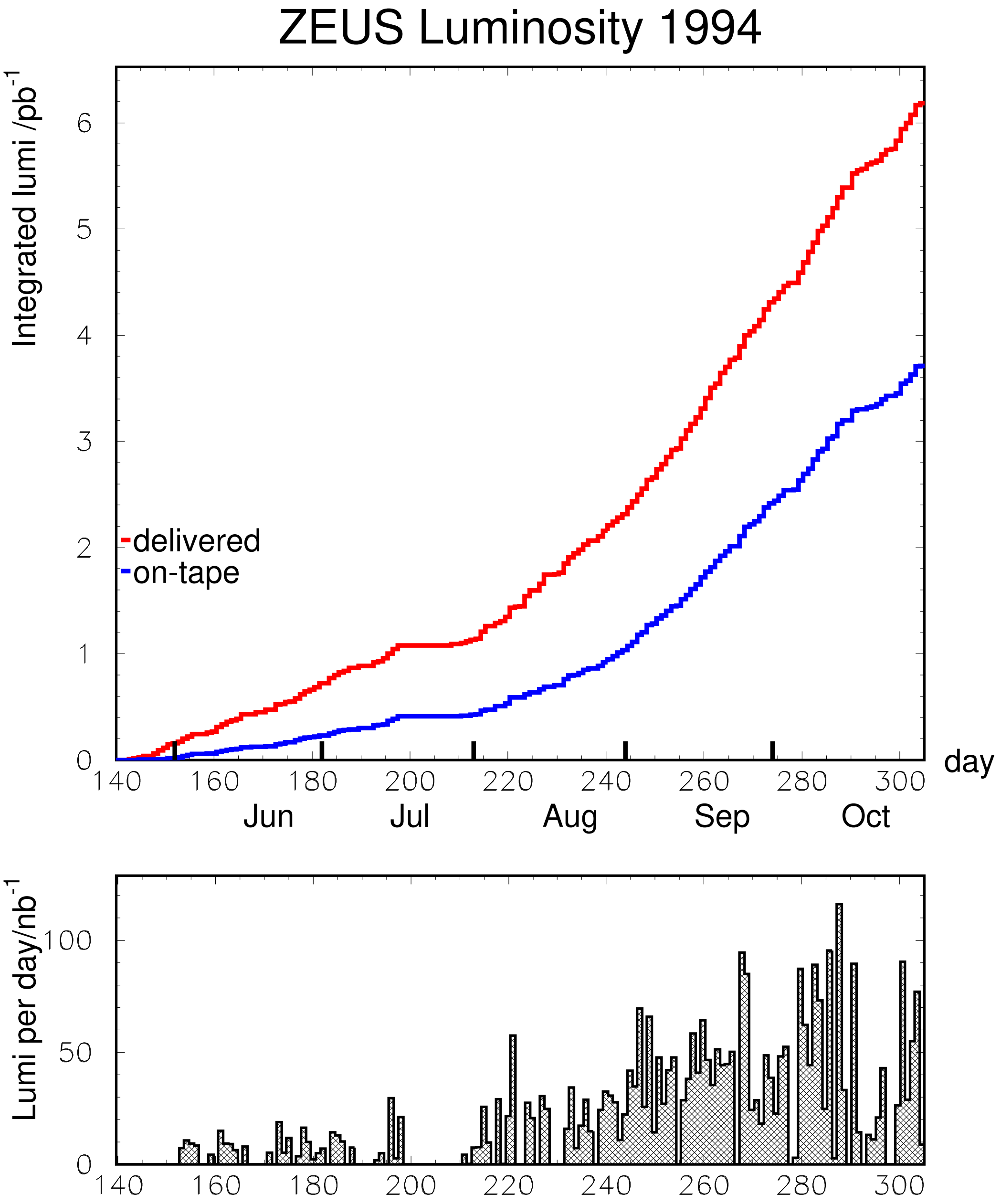

Figure 6: ZEUS luminosity 1994 delivered by HERA and recorded on tape.

Table 3: Contributions to the Error of the Luminosity Measurement.

	$ep \to e'\gamma p$ rate measurement		'Observed' cross-section determination
a.	*egas* background subtraction	a.	cross-section calculation
b.	correction for multiple events	b.	acceptance correction
c.	counting errors	c.	energy scale errors

luminosity trigger was changed from $E_\gamma > 5$ GeV to $16 > E_\gamma > 10$ GeV.

3.3 Offline Calculations

The offline luminosity determination was, as previously, based on data from the environmental records. The procedure was highly improved in comparison with the 1993 version. Instead of using the DESY IBM main-frame, a program performing luminosity calculations was installed on the ZEUS offline ZOW cluster. Every evening an automatic batch job was submitted to check whether new data files were available and, if so then the separate job started for each ZEUS physics run. The program was functionally divided in two stages. In a first part the proper energy calibration constants were determined (see [5]). The second part of the program performed the standard luminosity analysis, described in [1]. The actual calibration constants and pedestal values were used to correct the energy scale. Corrections for the geometrical acceptance, based on the data from the photon position detectors, were made using a two-dimensional acceptance matrix, same as in 1993. Luminosity values were also corrected for the multiple bremsstrahlung events within one bunch collision (pile-up effect).

The procedure was functioning reliably and failed only for a few runs which did not contain valid environmental data. Those runs were short and usually, due to corruption of the other data, were not classified as valid physic runs. During the running period a more sophisticated and improved version of the calibration procedure was developed and all runs were re-processed in November 1994 allowing for release of the preliminary list of the offline integrated luminosity already by the end of 1994.

4 Error of the Luminosity Measurement

4.1 Sources of the Systematic Errors

As was discussed in [1] the contributions to the luminosity error can be classified as it is shown in Tab. 3.

4.1.1 Errors in $ep \to e'\gamma p$ Rate Measurement

a. Uncertainty in *egas* background subtraction

Since a ratio of currents (a total electron beam current to total current of electron pilot bunches), k, is used in the procedure of the *egas* background subtraction (see [1]), therefore the error of the k measurement contributes to the error of the measurement of the rate of ep bremsstrahlung events and then to the luminosity uncertainty. In Fig. 7 *egas* rates normalized with bunch currents, R^{norm}_{egas}, are shown for 'trains' of pilot bunches in three runs (the change of the average normalized rate from run to run reflects mainly the change of the rest gas pressure in a HERA beam pipe close to the IP). Additionally, also plots of specific rates, $R^{spec}_{ep} = R_{ep}/(I_e I_p)$

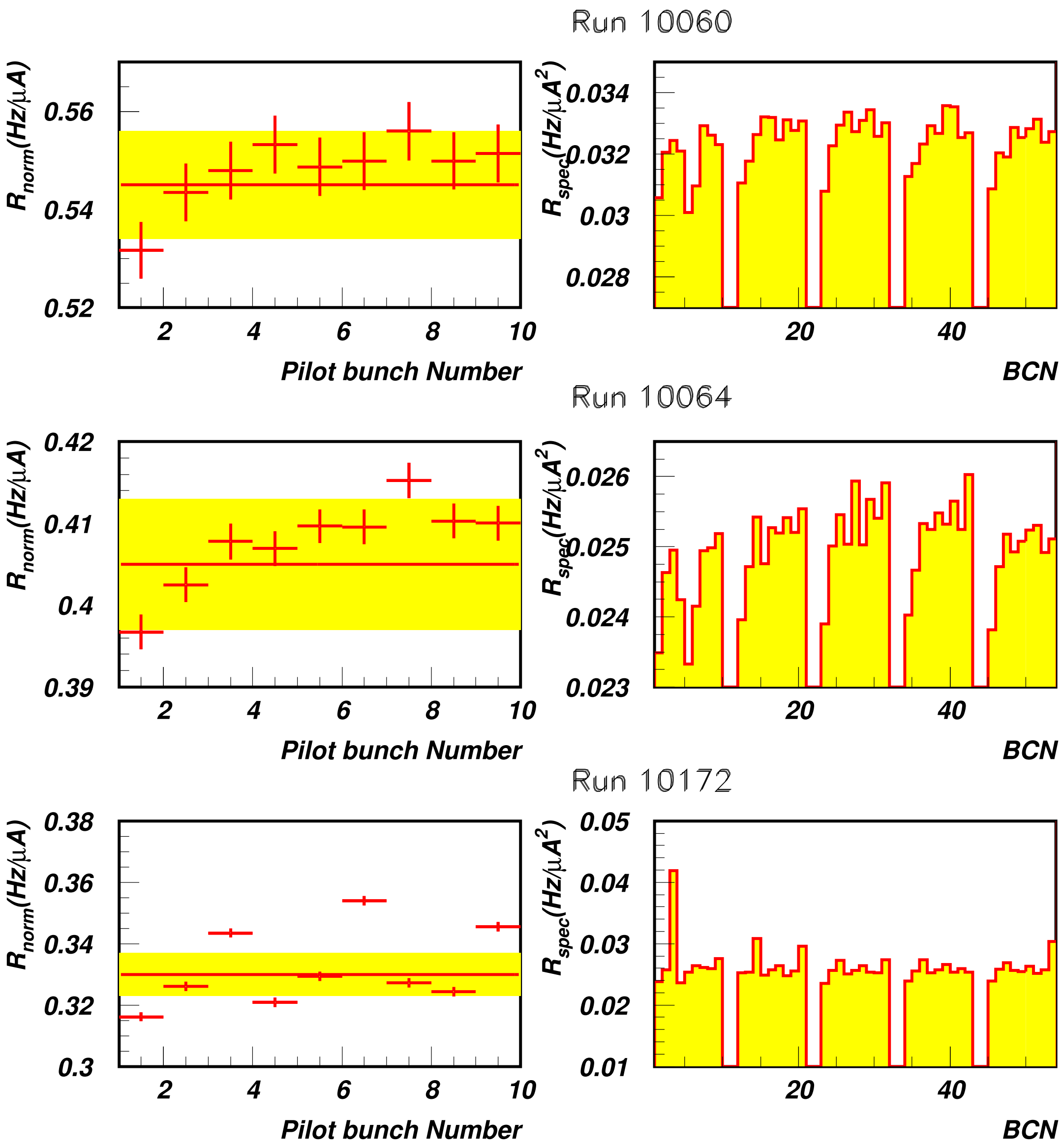

Figure 7: Average rates, R_{egas}^{norm}, of $egas$ bremsstrahlung events from electron pilot bunches normalized with electron bunch currents (solid lines show an average value and shaded area covers a $\pm 2\%$ range from average); and specific rates, R_{ep}^{spec}, of ep bremsstrahlung events from colliding bunches normalized with products of electron and proton bunch currents.

for colliding bunches are shown. In run 10172 strong fluctuations of R_{egas}^{norm} and R_{ep}^{spec} were observed for bunches with small electron currents (8–20 μA)[2].

All plots exhibit similar behavior – lower normalized rates at the beginning of a bunch train and higher normalized rates for bunches with small currents (in vicinity of bunches with larger currents – indicating strong pileup or baseline shifts in the bunch current measurement). As the typical normalized $egas$ rates differ systematically from bunch to bunch at a 2% level, this was taken as an estimate of the accuracy of the k factor measurement. Since the average contribution of $egas$ events was 14%, this resulted in a 0.3% uncertainty of the $egas$ background subtraction.

The error in $egas$ background subtraction could also emerge due to variation of some relevant parameters as pedestals, beam tilt, etc. with bunch crossing number. However, no significant differences were found between colliding and pilot bunches.

[2]For even smaller bunch currents quite serious problems appear in deciding which bunch is a pilot (unpaired) bunch and which is not. Actually, two different strategies were used – in off-line calculation no attention was paid whether there is some small proton current for proton beam buckets corresponding to electron pilot bunches or not; on the other hand in the on-line (final) algorithm such proton currents (if present) were taken seriously and included in $egas$ background subtraction [7].

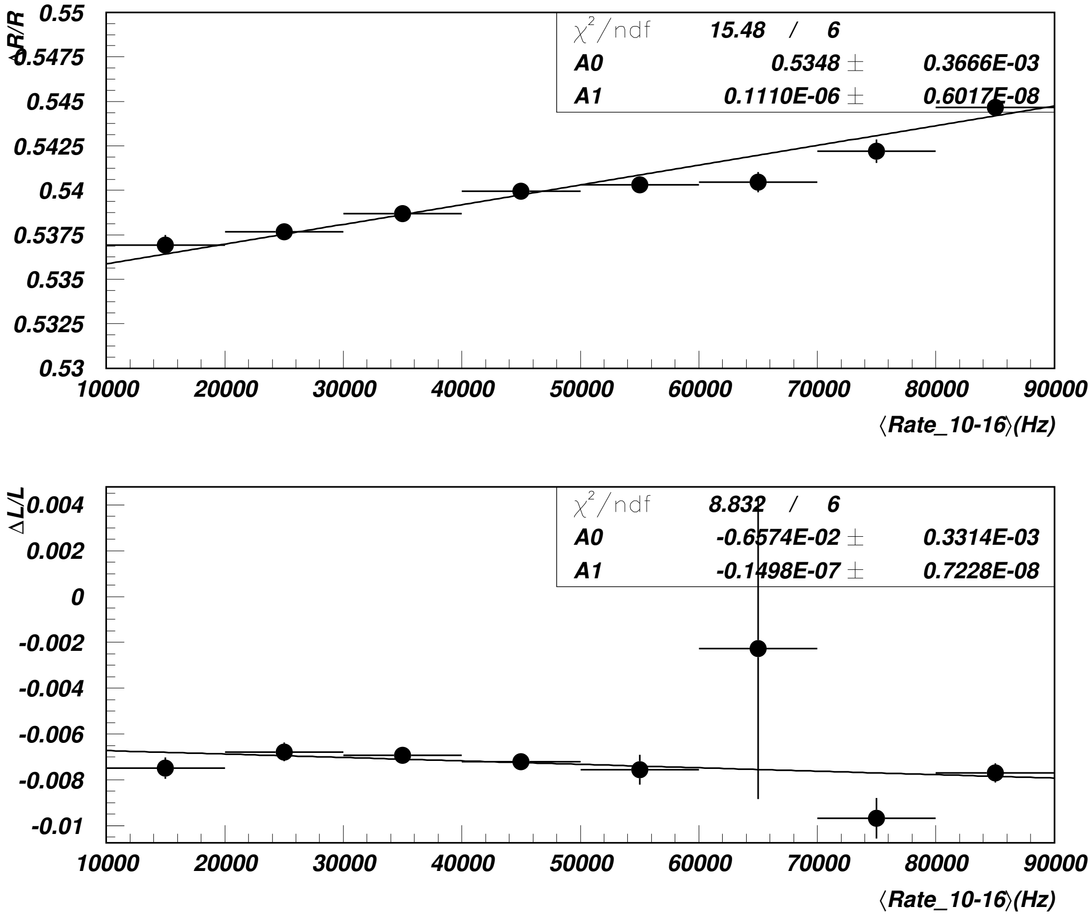

Figure 8: Relative differences, $\Delta L/L$ and $\Delta R/R$ between integrated luminosities L_5 and L_{10} and event rates $Rate_5$ and $Rate_{10}$ measured with $E_\gamma > 5GeV$ and $E_\gamma > 10GeV$ triggers plotted as a function of the average bremsstrahlung rate for $16 > E_\gamma > 10GeV$.

b. Counting errors

The counting errors can occur due to wrong flagging of the 'luminosity events' or malfunctioning of scalers which count such events. These errors were common for on-line and off-line measurement and were monitored for the nominal triggers ($E_\gamma > 5$ GeV and $16 > E_\gamma > 10$ GeV) by comparing readings from three independent scalers (see [1] for details). It was found to be negligible.

c. Multiple events effect

For $E_\gamma > 5GeV$ trigger the correction for this effect is negligible but for other types of luminosity triggers sizable corrections were applied using the correction factors from Tab. 2. In Fig. 8 the relative rate difference, $\Delta R/R = (Rate_5 - Rate_{10})/Rate_5$, and relative luminosity difference, $\Delta L/L = (L_5 - L_{10})/L_5$, are shown as a function of average bremsstrahlung rate, $\langle Rate_{10-16} \rangle$.

The clear dependence of the relative difference of 'raw' rates on the average bremsstrahlung rate disappears almost completely after correcting for multiple events in luminosity calculation.

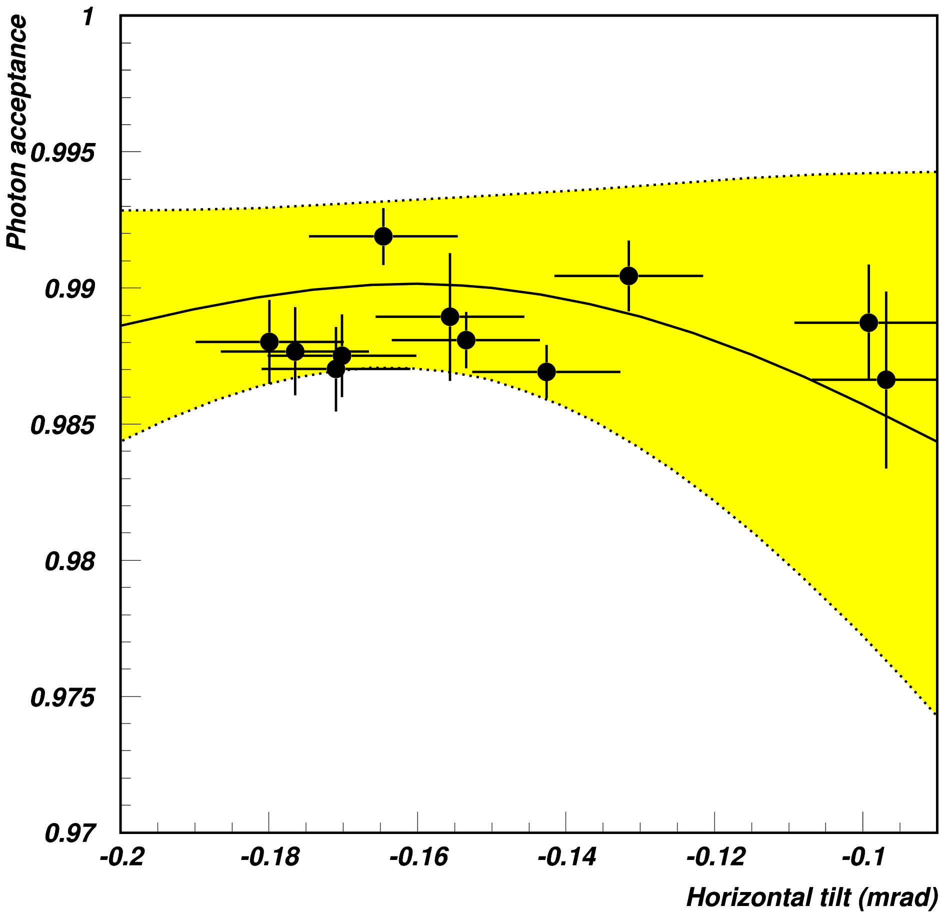

Figure 9: The measured (data points with statistical errors) and predicted (solid line with hatched area indicating the systematic uncertainty) photon acceptance as a function of the horizontal tilt of the e^+ beam.

Based on this result, we estimate error due to pileup events to be below 0.1%, i.e. less than 10% $\times$ typical correction for $E_\gamma > 10GeV$ trigger.

4.1.2 Uncertainty in determination of the observed cross-section

a. Theoretical cross-section

The higher order corrections to the Bethe-Heitler cross-section (obtained in Born approximation) are small, of the order of 0.3% [8, 9, 10, 11], and since they partially cancel out, the total correction is negligible, below 0.2%. However, the calculations were done for different kinematical cuts than cuts actually used for selection of the luminosity events, therefore, a 0.3% error due to higher order corrections the correction was assumed. The other correction to the Bethe-Heitler cross-section is needed due to finite lateral sizes of HERA [12]. Recently, the theoretical predictions (which is used in the fast MC simulation) for this effect at HERA has been verified to about 0.9, 0.3, 0.1, 0.2% for four triggers, respectively [6]. The total theoretical error was obtained by adding linearly these two uncertainties.

b. Acceptance error

The acceptance derived from the MC simulation was checked with the use of a method involving bremsstrahlung tagging with the *ecal* (see [13]). The systematic uncertainties in this

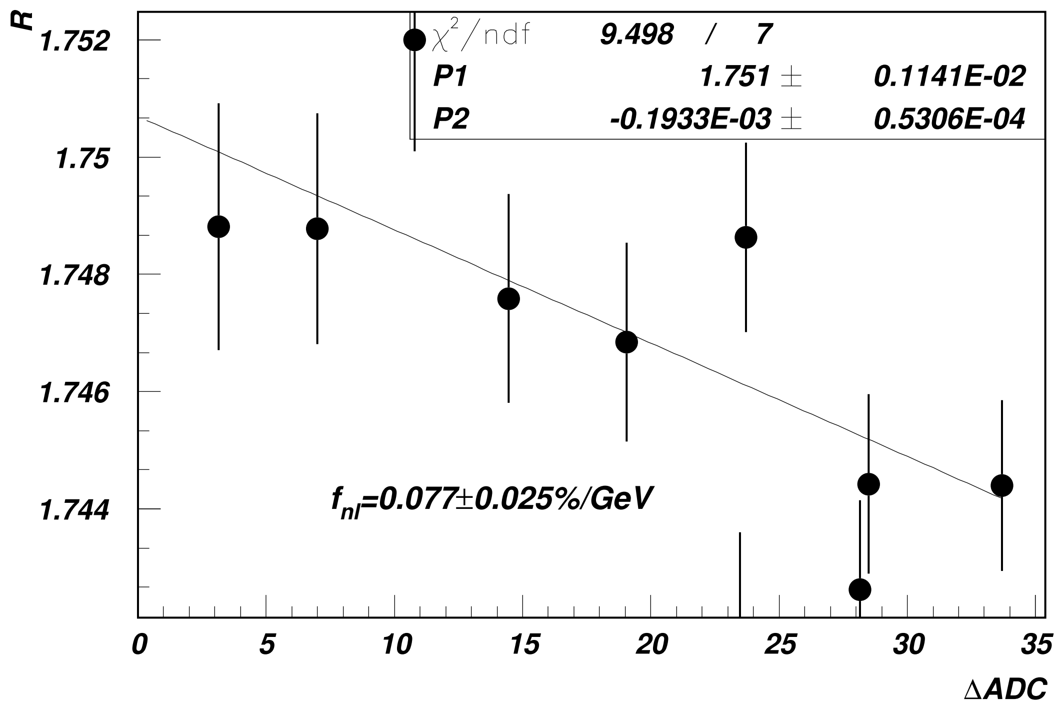

Figure 10: Plot showing deviation from linear behavior of the front-end electronics for one (of two) photon channels, R is a ratio of the measured LED pulses with two fixed amplitudes at nine slightly different HV settings for the photomultiplier (one step corresponds to 0.5% HV change) where ΔADC is the difference in ADC counts for the two measured LED pulses (at given HV setting) – perfectly linear electronics should have R independent on ΔADC, therefore an observed slope was taken as a measure of the non-linearity in the LUMI front-end electronics.

method were due to correction for *egas* bremsstrahlung contribution and deformation of the angular distribution of the tagged photons, and were below 0.2% for tilts (with respect to the nominal direction of the highest acceptance) below 0.1 mrad [13]. In Fig. 9 the photon acceptance measured in this way is compared with the MC predictions showing a good agreement.

This comparison as well as the estimation of the systematic error of the acceptance prediction (see [1]) showed that a 0.4% acceptance uncertainty for typical tilts of the electron beam ($-0.2 > t_x > -0.1$ $mrad$ and $-0.1 > t_y > 0.1$ $mrad$) is expected.

c. Uncertainty in energy scale

A 1994 calibration procedure of the LUMI calorimeters is discussed in detail in [5]. The systematic error of the fitting procedure used for calibration was checked by comparison of the results of the nominal calibration procedure [5] with the calibration procedure used in [6]. First procedure used ep data, did not use E_{sh} parameter describing energy loss in the filter and was fitting the non-linearity parameter f_{nl}, whereas the second procedure used egas data, did use E_{sh} parameter and had f_{nl} parameter fixed (and different cuts, binning, bin corrections, etc.). Both procedures gave the same results within $\pm 0.3\%$ what was taken as a systematic error of the fitting procedure. Other contributions to the uncertainty of the photon energy scale were due to non-linearity in electronics (including uncertainty of the FADC threshold value), pedestal uncertainty and calorimeter non-linearity due to energy losses in the carbon filter.

A $0.07\%/GeV$ non-linearity of the whole readout chain was established using LED pulse data, see Fig. 10. Laboratory tests of the FADC cards [14] confirmed these results and showed

Table 4: Luminosity uncertainty (in per cent) due to energy scale errors for four luminosity trigger types (uncertainties with * correspond to the final filter configuration)

Error type	Trigger type			
	$E_\gamma > 2$	> 5	> 10	$16 > E_\gamma > 10 GeV$
Fitting uncertainty (±0.3%)	0.1	0.2	0.3	0.1
Pedestal uncertainty (±0.1)*	0.45	0.25	0.2	0.15
Non-linearity in electronics (±0.02%/GeV)	0.2	0.3	0.4	0.35
FADC threshold value (±0.2)	0.9	0.5	0.4	0.45
Calorimeter non-linearity (±0.025 GeV)*	0.7	0.4	0.3	0.25
Total error	1.45	0.95	0.9	0.65

that this is actually due to non-linearity in fast current integrators. The estimated error of this parameter is $\pm 0.02\%/GeV$ [3].

The calorimeter non-linearity was mainly due to the presence of the carbon absorber shielding against synchrotron radiation. The MC simulation showed that for the relevant range of photon energies ($27 > E_\gamma > 2\ GeV$) the absorber causes a shift of the average energy deposited in the γcal by respectively 0.15, 0.025 and −0.11 GeV (see [15]) for three filter configuration. If such a constant shift is implemented into the fitting procedure as a free parameter it improves significantly a quality of the fit allowing for verification of the MC predictions using high statistics data of *egas* events for the last filter configuration (see [6]). The difference of 25 MeV between measured and expected values of the energy shift was taken as an estimate of uncertainty (for first and second filter configuration the error was doubled since no comparison with data was possible). On the other hand, the deterioration of the calorimeter energy resolution was not relevant in the luminosity measurement and no indication was found for other detector effects which could significantly affect photon energy measurement.

The understanding of the energy scale was also checked by taking test data at 12 and 27.5 GeV and fitting the bremsstrahlung spectra. The calibration constant were then corrected for changing gain of photomultipliers using LED test pulses (about 1% effect). The corrected constants agreed within statistical error of 0.8%.

The actual FADC threshold value was monitored with charge injection tests as described in [1]. The correction due to non-nominal threshold value was known to ±0.2 ADC counts.

Pedestal value was monitored separately for colliding and pilot electron bunches. The typical difference for runs with the final filter configuration was below 0.1 ADC counts and below 0.3 ADC counts for first and second configuration. This was taken as an estimate of the pedestal uncertainty.

The total error shown in Tab. 4 due to the energy scale uncertainties was estimated by adding all contributions in quadrature.

4.2 On-line Luminosity Measurement

In 1994 the final on-line luminosity calculation involved the subtraction of *egas* background, corrections for non-nominal tilt of the electron beam (i.e. $t_x = -0.15, t_y = 0\ mrad$), pedestal shifts and event pileup. No correction for variation of the γcal calibration constant was applied. In Fig. 4.2 the relative difference between integrated luminosities calculated online and offline

[3] Preliminary results of 1995 measurements of the bremsstrahlung spectra of 12 and 27.5 GeV positron beams confirmed the estimate of non-linearity in electronics to $\pm 0.015\%/GeV$.

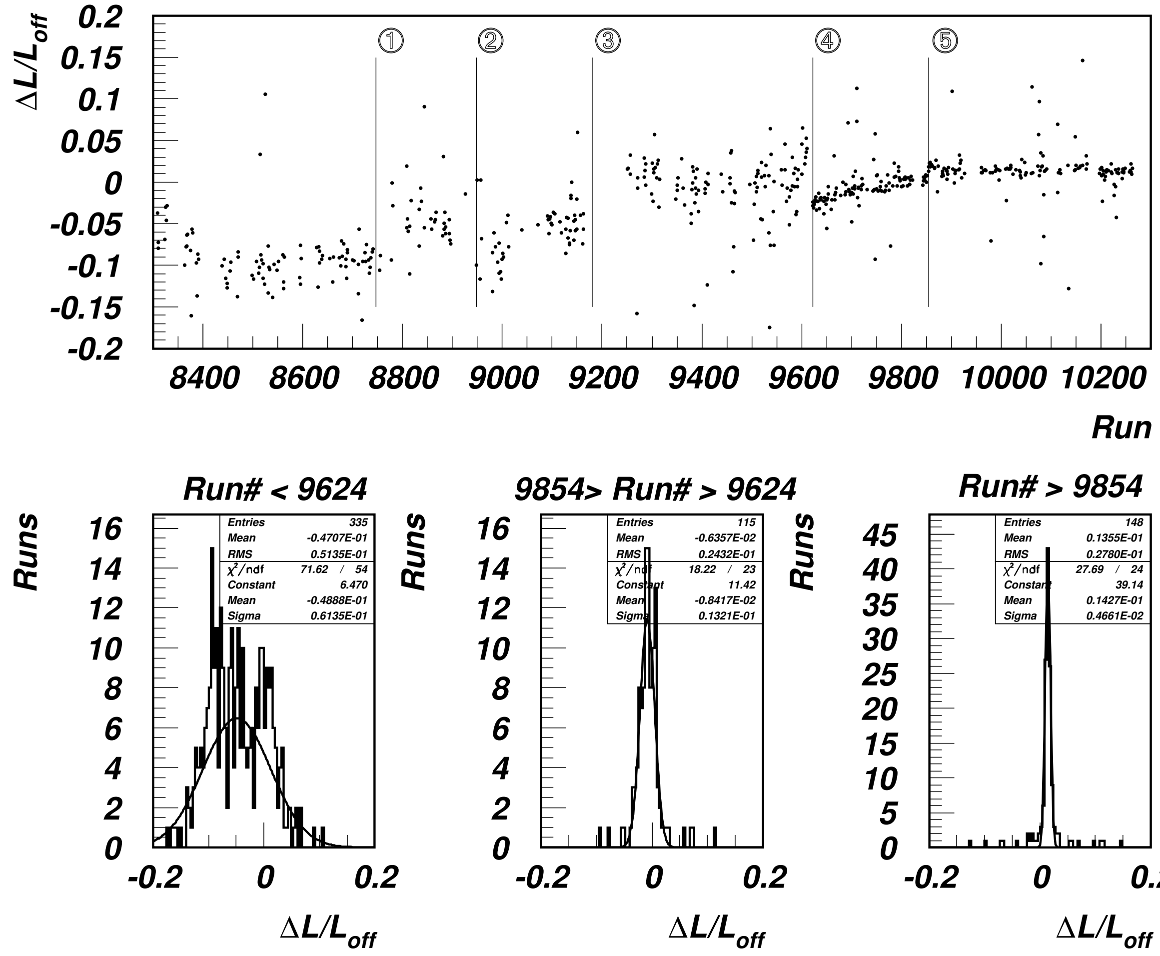

Figure 11: History of the relative difference between online and offline integrated luminosities, $\Delta L/L$ (labels indicate experimental changes: 1 – on-line constants corrected, 2 – pedestal jump, 3 – change of filter configuration to 'b' and pedestal jump, switch to positrons, 4 – change of filter configuration to 'c' and switch to the new on-line algorithm, 5 – switch to the $16 > E_\gamma > 10$ GeV trigger); and distributions of the difference for three run ranges showing improvement of the on-line algorithm.

are shown after dead-time correction. If one assumes that the offline measurement is much more accurate than the online one, then the widths and offsets of these distributions directly reflect the error of the on-line measurement. The last distributions, obtained for runs when final version of the on-line luminosity procedure was used, shows that a 2% precision of the on-line measurement was achieved.

4.3 Off-line Luminosity Measurement

The offline luminosity determination in 1994 involved a number of corrections described in Sec. 3. According to the discussion of in Sec. 4.1, the contributions to the systematic error of the luminosity measurement can be summarized as shown in Tab. 5. Since all contributions are to a good approximation independent on one another, therefore errors can be summed up in quadrature resulting in a 1% total systematic error of the ZEUS luminosity measurement in 1994 (valid for final filter configuration; 1.2% uncertainty should be used for first two filter configurations).

In Fig. 12 the luminosity measured with the $E_\gamma > 5$ GeV trigger is compared with the luminosities measured with three other trigger setups. The average and width of the distribution

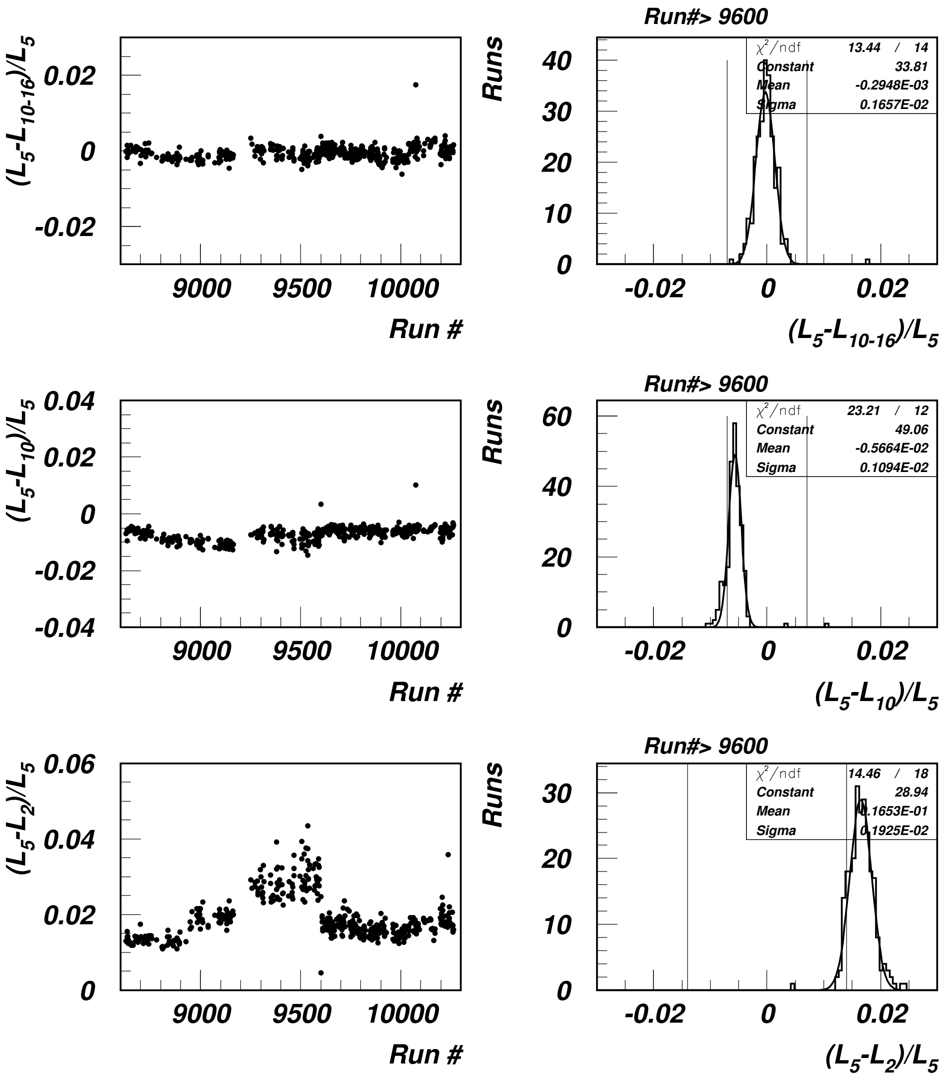

Figure 12: Histories of the relative differences between the reference luminosity, L_5 ($E_\gamma > 5GeV$ trigger), and luminosities measured with three other triggers (L_2, L_{10} and L_{10-16}, with $E_\gamma > 2$, $E_\gamma > 10$ and $16 > E_\gamma > 10GeV$ triggers, respectively); and distributions of the relative differences for runs with the final filter configuration (run#>9600) where systematic errors are indicated by vertical lines.

Table 5: Systematic error of the luminosity measurement in 1994.

Contribution	Trigger type			
	$E_\gamma > 2GeV$	$E_\gamma > 5GeV$	$E_\gamma > 10GeV$	$16 > E_\gamma > 10GeV$
egas background subtraction	0.3%	0.3%	0.3%	0.3%
Correction for multiple events	0.1%	0.1%	0.1%	0.1%
Counting errors	$< 0.1\%$	$< 0.1\%$	$< 0.1\%$	$< 0.1\%$
Cross-section calculation	1.2%	0.6%	0.4%	0.5%
Acceptance correction	0.4%	0.4%	0.4%	0.4%
Energy scale errors	1.45%	0.95%	0.9%	0.65%
Total systematic error	1.95%	1.25%	1.1%	1.0%

of the relative difference between them is a measure of the luminosity errors except common ones (as acceptance and, to some extend, counting and *egas* background subtraction errors). The comparison shows that all measurements are consistent within systematic errors. The luminosity measured with the $E_\gamma > 2$ GeV trigger seems to be, however, lower than luminosities measured with three other triggers. This was also observed in 1993 and since was not observed in comparison of *egas* data, therefore it is most probably due to higher than expected beam-size correction (as was also observed in [6]) and additional suppression due to radiative corrections.

We want to stress that the quoted 1% precision refers to the luminosity measurement without correction on contribution due to proton satellite bunches. Since the luminosity measurement is not sensitive to the proton beam timing, therefore the measured luminosity contain without any weight contributions from main and satellite proton bunches. The correction on satellite bunches (which depends on the type of physics analysis) may significantly deteriorate the final error on normalization.

4.4 Conclusions

A comparison of the present analysis with the study of systematic errors of the luminosity measurement in 1993 running period shows that an improvement in the accuracy (from 2.5% to 1%) was achieved thanks to:

- improved understanding of the measurement of photon energy – measurements of the non-linearity in electronics, verifying predictions of the MC simulations for energy losses in dead material in front of the photon calorimeter, better experimental set-up (the new vacuum pipe and moving the carbon filters towards γcal) – error decreased from 2% to 0.7%;
- better understanding of theoretical corrections – error decreased from 1% to 0.5%,
- smaller *egas* background – error decreased from 0.5% to 0.3%.

The accuracy of the on-line measurement improved significantly from about 7% to 2% after applying on-line corrections for pedestal shifts, acceptance changes and event pileup.

5 Outlook

There are two major contributions to the systematic error of luminosity measurement: energy scale errors and theoretical uncertainties. We foresee following measures to suppress them further. First, the re-calculation of higher order corrections with appropriate experimental cuts is planned using existing software due to M. van der Horst [8, 9]. This with presumably better understanding of the beam-size effect could lead to much smaller theoretical error. Secondly, new 10-bit FADC boards are designed and should be installed in the 95/96 winter shutdown. This should make the binning errors ('FADC threshold') negligible as well as improve pedestal determination. Thirdly, a design of the new photon detector is under preparation. The new detector would allow for better control of absorber effects, have much better energy resolution (which makes the calibration fits more reliable) and sensitivity to low energy photons. The detector would have also much bigger robustness for radiation damage hence have longer durability and equal performance even at the highest instantaneous luminosities.

Assuming all these improvements are done and careful control of the egas subtraction, acceptance and pileup effects (significant at the nominal luminosity) is performed, we believe that lowering (in two years perspective) of the luminosity uncertainty to a 0.5% level is feasible.

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