Off-line Luminosity Calculation in the ZEUS Experiment in 1997, 1998 and 1999

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1 Introduction

The luminosity determination is based on the detection of the *ep* bremsstrahlung events. Therefore the basic component of the luminosity monitor is the photon detector consisting of:

- a 1.5 mm thick copper berylium exit window from a proton beam pipe at 92.5 m from the interaction point (IP);
- an absorber (filter) of the variable thickness: $0.5 \div 3\ X_0$ ($1X_0 = 1$ radiation length) used as a shielding against a large flux of direct synchrotron radiation. Since 1997 $3X_0$ filter ($2.5X_0$ C and $0.5X_0$ Pb) is used;
- $24X_0$ deep lead-scintilator electromagnetic calorimeter at 106 m from the IP. Inside the calorimeter at the depth of $3X_0$, a position detector consisting of two crossed layers of scintillator fingers is installed.

To estimate the photon energy the ADC counts from the two energy channels (which correspond to the top and bottom wave length shifter readouts of the calorimeter scintillators) are recorded. For the luminosity determination their arithmetic average is used.

The luminosity monitor includes also an electron calorimeter, measuring the energy of the electron in coincidence with the photon from the same bremsstrahlung event. It can serve for consistency checks but is not used directly for the luminosity measurement.

The data from the luminosity monitor are collected in so called environmental records. These data comprise the readouts from the scalers used for the on-line luminosity measurement and from additional 96 scalers available in the ZEUS first level trigger system (GFLT) as well as the data used for the calibration and monitoring purposes.

More precisely these are:

- for luminosity measurement:
  - 32 GFLT scalers counting bremsstrahlung photons for 8 different cuts on the photon and/or electron energies for all bunches with and without dead time correction.
  - 64 scalers counting bremsstrahlung events separately for 64 selected bunches;
  - total time;

- trigger dead time;
- beam currents;

- for monitoring and calibration, the samples of ADC distributions for:
  - electron pilot bunches;
  - colliding bunches;
  - pedestals (random trigger);
  - LED pulser (flashed during empty HERA bunch crossings – so called light test);
- the position detector data.

The environmental records are taken every 16 seconds.

The history of the development and more detailed description of the luminosity monitor and the data aquisition system can be found in [1-4].

2 Luminosity Determination

The luminosity L is defined by the relation

$$R = L\sigma \tag{1}$$

where R is the rate of the process with the cross section σ. Therefore to determine L from rates of bremsstrahlung photons selected by various cuts and corrected for the possible background processes, one has to calculate the fractions of the observed of bremsstrahlung cross section σ_{obs} corresponding to these cuts and to the geometrical acceptance of the detector.

As a measure of the calorimeter energy the average of the two readouts (top and bottom) after subtracting the ADC pedestals is used:

$$ADC_{cal} = (ADC_{top} + ADC_{bottom})/2 - (ADC^{ped}_{top} + ADC^{ped}_{bottom})/2 \tag{2}$$

In ideal case

$$ADC_{cal} = c_{conv} * E_{cal} \tag{3}$$

where c_{conv} is a conversion constant from GeV to ADC counts, however small nonlinearities both differential (nonequal ADC bins) and integral are observed and have to be corrected for. C_{conv} depends of course on the gain of the used PM high voltage and it may be chosen according to the needs. The generally accepted procedure is to choose it such that the whole expected energy spectrum fits well inside the dynamical range of the applied ADC convertors (256 counts for 8 -bit convertor) and that number of counts per 1 GeV assures the required accuracy of energy neasurement. In our case $C_{conv} = 7GeV^{-1}$ was chosen and it will be called in further the nominal calibration constant. In parallel the pedestal values measured at the same HV will be called nominal.

For the luminosity determination the following GFLT scalers are used (E_γ denotes the incident photon energy, E_{cal} denotes the calorimeter energy which is transformed to ADC counts):

- counting events with $E_{cal} \geq E_{cal}(ADC\ counts = 25)$ (equivalent to $E_\gamma > 2GeV$ cut for nominal calibration);

- counting events with $E_{cal} \geq E_{cal}(ADC\ counts = 46)$ (equivalent to $E_\gamma > 5GeV$ cut for nominal calibration);

- counting events with $E_{cal} \geq E_{cal}(ADC\ counts = 81)$ (equivalent to $E_\gamma > 10GeV$ cut for nominal calibration);

- counting events with $E_{cal} \geq E_{cal}(ADC\ counts = 81)$ and $E_{cal} \leq E_{cal}(ADCcounts = 123)$ (equivalent to $10GeV < E_\gamma < 16GeV$ cut for nominal calibration);

- counting events flagged by the LUMI hardware as bremsstrahlung.

Corresponding σ_{obs} is calculated as

$$\sigma_{obs} = A \int_{E_{cal}(ADC_{min})}^{E_{cal}(ADC_{max})} dE_{cal} \int_{0.1GeV}^{E_{beam}-M_e} \sigma_{BH}(E_\gamma) P(E_\gamma, E_{cal}) dE_\gamma \tag{4}$$

where $\sigma_{BH}(E_\gamma)$ is the Bethe Heitler bremsstrahlung cross section corrected for the beam-size effect [5]. $P(E_\gamma, E_{cal})$ denotes the calorimeter response function which gives the probability that for the incident photon energy E_γ the calorimeter energy is E_{cal}. This function depends on the calorimeter readout energy smearing and the effects of the absorption of the photon energy in the filter. ADC_{min} and ADC_{max} denote the thresholds used in the scalers.

The function $E_{cal}(ADC)$ is the transformation of the ADC counts to the energy and depends on the properties of the electronics readout system.

The photon detector geometrical acceptance A is limited by the proton beam line apertures and depends on the electron beam tilt and beam divergence and is varying from 0.978 for the nominal beam tilt and typical divergence (0.2 mrad) to about 0.95 for the beam tilts ± 0.1mrad in x direction. The procedure of finding the effective aperture is described in [2]. It was repeated in 1998 with the higher statistics data of special test runs where the beam tilt was varied in wide range. The results of [2] were confirmed [4]. The acceptance A is estimated using a Monte Carlo program, which for a given beam tilt and beam divergence calculates the fraction of the bremsstrahlung photons which can reach the detector.

The rates have to be corrected for:

- more than one bremsstrahlung photon during one bunch crossing. In such a case a sum of energies of all photons is measured (event pile-up). A correction is calculated basing on Monte Carlo prediction;

- contamination of e-gas bremsstrahlung, which is estimated from the rates observed for electron pilot bunches, under the assumption that this background scales with the electron beam current. In the running period 1998/99 this fraction was about 2%.

Other possible sources of background signals either affect the spectra only in its low energy part (e.g. proton beam halo, backscattering off the thermal photons in the Compton process), or are negligible.

3 Calorimeter Response and Electronics Readout

The general form of the photon detector response function $P(E_\gamma, E_{cal})$ has been derived from the results of the EGS4 simulation. E_{cal} - the energy finally deposited in the calorimeter depends on the precise scheme of the photon detection i.e. if there is a filter or preshower and how both are constructed and what type of calorimeter is used. In our case we used the sandwich lead/scintillator calorimeter preceeded by a filter of variable thickness. This modifies the measured E_{cal} by introducing a shift of energy due to the loss inside the filters and distorts the shape of the deposited energy spectrum.

Since the EGS4 study shows that for filters of the thickness $(0.5 - 3.0)X_0$ it is sufficient to introduce one energy smearing function and then to correct for the energy loss in the filter, a new response function $P(E_\gamma, E^{'})$ need to be used. $E^{'}$ is the intristic calorimeter energy deposit, which if no filter is present $E^{'} = E_{cal}$ and the shape of E_{cal} distribution is gaussian. Although it remains gaussian for filters thiner than $2.5X_0$, for filters $> 3.0X_0$) it becomes asymmetric (see fig.1).

For the running period 1997-1999, $3X_0$ filter was used and the new form of the response function is needed. It turns out that the properly transformed gamma distribution describes the spectrum well:

$$P(x, E') = A_{norm} * (x - E')^{\alpha-1} * e^{-\beta(x-E')}, \tag{5}$$

where

$$x = E_\gamma + (\alpha - 1)/\beta,$$

$$\alpha = 19.5$$

A_{norm} is the normalization factor,
and β can be expressed in terms of the standard energy resolution of the calorimeter σ_0 :

$$\beta = \sqrt{\frac{\alpha}{(x * \sigma_0^2 + 0.3)}} \tag{6}$$

The value 0.3 appearing in (6) takes into account the observation that the smearing for low photon energies is relatively wider. From the distribution (5) the values of the variable $E^{'}$ can be sampled, from which after correcting for the energy loss in the filter, the calorimeter energy E_{cal} can be calculated:

$$E_{cal} = c_1 * E' + c_2 * E'^2 - E_f \tag{7}$$

where E_f, c_1, c_2 are constants. The quadratic term is very small. This formula works well for photon energies above $2GeV$.

The actual widths of ADC bins were measured [2]. For the calibration, the measured ADC counts are substituted by the corrected ones, obtained in following procedure: for each ADC bin its contents is smeared by an uniform distribution through its true width ($ADC_{cal} = ADC_{loweredge} + rndm * ADC_{binwidth}$, where rndm is a random number uniformly distributed between 0 ans 1.) and the resulting values are histogrammed in bins of equal size. For the luminosity measurement this non-linearity is taken into account by using actual limits in the integration in (4).

The integral non-linearity modifies (3) to :

$$ADC_{cal} = c_{conv} * E_{cal} - c_{nl} * E_{cal}^2 \tag{8}$$

Comparing (8) and (7) it is seen that linear (c_γ, c_1) and quadratic (c_{nl}, c_2) terms describing the effect of the filter and the electronic readout are correlated and hence cannot be determined separately. Therefore only one formula is used:

$$ADC_{cal} = c_\gamma * (E' - E_f) * [1 + f_{nl}(27.5 - E')] \tag{9}$$

For convenience, the non-linearity parameter f_{nl} was introduced in such a way that for the highest photon energies quadratic term can be neglected. Since the non-linearity f_{nl} matters primarily in the middle of the energy spectrum it can be derived more accurately from the data at lower energies. In particular, by using the data collected at 12 GeV electron beam. The middle part of the spectrum at 12 GeV has more structure then that at 27.5 GeV and is more sensitive to f_{nl}. Now c_γ is the overall calibration constant.

4 Calibration

The description of the calorimeter presented in the previous section contains 4 parameters which have to be found by fitting the predicted ADC distributions to the real data.

The parameters E_f, σ_0, f_{nl} are time independent (neglecting the radiation damages). Their accurate knowledge is essential for the luminosity calculation. The $e - gas$ bremsstrahlung energy spectrum has the reduced pile-up effect (due to the relatively low event rates) and is free from the effect due to the proton beam halo. For these events the beam size effect is not present. It is therefore best suited to fit for finding these parameters, even though the remnant gas in the beam pipes is not precisely known (it is assumed that $< A >= 4.2$).

The ep bremsstrahlung photon spectrum for a typical run is shown in fig 2. The nominal value c_γ is 7 GeV^{-1}, but as well as the values of the pedestals (for which the nominal value is ~ 11.5), it changes in time, even during one run. From each group of 10 environmental records the average pedestal and light test values are taken. The actual pedestal values are subtracted and ADC counts are scaled according to the change of the gain as shown by the light test. In this way the data from all environmental records, even for the long run can be combined. The value of the calibration constant c_γ given for the run corresponds to the conditions while taking the first group of the environmental records. The current value of c_γ during the run is:

$$c_\gamma^{real} = c_\gamma * < ADC_{light\ test}^{current} > / < ADC_{ligh\ test}^{begining\ of\ run} >$$

With the help of the light test it can be ensured that the gain in 27.5 and 12 GeV test runs is the same.

For the calibration of the photon detector with $3X_0$ filter the test data were taken in January 1999. The observed e-gas bremsstrahlung spectra are shown in fig.3 . In the low energy part (especially for the 27.5 GeV data set) of the measured spectra, (which was not included in the fit) a significant contribution from the thermal photons Compton scattering can be seen. Unfortunately, in the 12 GeV data an admixture of the multiple bremsstrahlung photons in the same bunch crossing is observed. This effect, even if it is taken into account in the fitting procedure, decreases the precision of f_{nl} determination.

The quality of the fits is good ($\chi^2/ndf \simeq 1.$). It is worth mentioning that the change of the assumed shape of calorimeter energy smearing from a gaussian to an asymmetric one improves χ^2 by about 20%.

The obtained parameters are listed in Table 1. In the same table the parameters obtained by fit to EGS4 data are shown. Having in mind that EGS4 does not describe the electronics non-linearity (in reality $c_{nl} \simeq 0.001$), a good agreement between the real data and the simulation is observed.

In the acceptable range of the parameters (i.e. within their errors) the observed cross sections vary by $\pm$ 0.9% for $10GeV < E_\gamma < 16GeV$ scaler.

	data		*EGS4*	
σ_0	0.323	± 0.005	0.306	± 0.006
E_f	0.380	± 0.025	0.422	± 0.020
f_{nl}	-0.0005	± 0.0004	-0.0015	± 0.0004
c_γ	6.936	± 0.003		

Table 1.

For the running period 1997 the non-linearity parameter f_{nl} was chosen to be -0.0005. After collecting the data for the whole period the consistency between luminosities obtained with the different scalers for $e - gas$ (obtained with the electron pilot bunches) was checked (fig. 4). The relative differences are small (about 0.2%) and they can be partialy due to inaccurate knowledge of non-linearity parameter f_{nl}. So, for the running period 1998-1999 f_{nl} was changed to -0.00015 (which is still within the acceptable range). There are indications that the calorimeter parameters may slightly depend on the incident photon hit position (see section 7). Such dependence introduces an extra uncertainty in the parameter determination and it should be further investigated. Although f_{nl} was not determined with a satisfactory precision, the previously used values: of 0.0011 for $2X_0$ filter and of 0.0007 for $2.5X_0$ filter are excluded by the present fit.

For the physics runs c_γ is found by fitting e-gas photon spectrum obtained for e pilot bunches starting from 7 Gev to avoid possible background effects in the low energy part of the spectrum. Remaining parameters are kept constant. For the majority of runs χ^2/ndf is about 1.

5 Determination of observed cross sections

For each scaler the integrals in formula (4) are calculated in the Monte Carlo program LUFAST [6] using the nominal values for the pedestal and the calibration constant and the remaining parameters describing the calorimeter response taken from the fits to the test data. In the further text they are referred as

$$\sigma^i_{LUFAST}(c_\gamma^{nominal}, ADC_{ped}^{nominal}),$$

where "i" distinguishes the scalers.

In LUFAST the bremsstrahlung photons are generated using the BREMGE generator [6], in which, the Bethe Heitler formula for the cross section is modified by the effect connected with the finite size of transverse beam dimension (beam size effect [5]). The strength of the beam size effect is controlled by the two parameters Δ_x and Δ_y corresponding to the widths of the beam spread in the transverse plane. Additionally, the photon spectrum distorted by the pile-up effect is generated. The other values needed for the observed cross section calculation are:

- Bethe Heitler cross sections integrated for all scalers separately in the limits defined by (9) for the nominal detector parameters: $\sigma^i_{BH}(c_\gamma^{nominal}, ADC_{ped}^{nominal})$.;
- Bethe Heitler cross sections integrated for all scalers for the real detector parameters (taking into account the variations during the run): $\sigma^i_{BH}(c_\gamma^{real}, ADC_{ped}^{real})$.;
- the correction for unequal ADC bins;
- the geometrical acceptance of the detector.

Real values of the pedestal and the calibration constant, as well as the geometrical acceptance depending on the beam tilt and divergence, can vary in the running period (even during single run) therefore for each scaler, the real values of the observed cross section are determined in the following way:

$$\sigma^i_{obs} = A * \frac{\sigma^i_{LUFAST}(c_\gamma^{nominal}, ADC_{ped}^{nomonal})}{\sigma^i_{BH}(c_\gamma^{nominal}, ADC_{ped}^{nominal})} * \sigma^i_{BH}(c_\gamma^{real}, ADC_{ped}^{real}) * C^i_{ADC} \tag{10}$$

where A is the geometrical acceptance and C_{ADC} is the factor correcting for the unequal ADC bins.

The calculation of the real observed cross sections is based on the assumption that the fraction:

$$\frac{\sigma^i_{LUFAST}(c_\gamma, ADC_{ped})}{\sigma^i_{BH}(c_\gamma, ADC_{ped})}$$

which can be interpreted as a correction due to the calorimeter response, is constant in the range of c_γ, ADC^i_{ped} occuring during the data taking. Monte Carlo calculations show that this assumption is correct and maximum deviations are less than 0.1%

The values needed for the observed cross sections calculations are summarized in Table 2 for both 1997 and 1998-1999 running periods.

		1997	1998 − 1999
c_γ		6.936	6.936
ADC_{ped}		11.3	11.3
E_f		0.38	0.38
σ_0		0.323	0.323
f_{nl}		-0.0005	-0.00015
$E_{electron\ beam}$		$27.54GeV$	$27.54GeV$
$E_{proton\ beam}$		$820GeV$	$920GeV$
Δ_x		$250\mu m$	$250\mu m$
Δ_y		$50\mu m$	$50\mu m$
σ_{LUFAST}	$ADC\ count \geq 46$	$65.563mb$	$66.222mb$
	$ADC\ count \geq 25$	$109.22mb$	$110.03mb$
	$ADC\ count \geq 81$	$35.498mb$	$35.912mb$
	$81 \geq ADC\ count \geq 123$	$17.880mb$	$18.063mb$
σ_{BF}	$ADC\ count \geq 46$	$67.5943mb$	$68.387mb$
	$ADC\ count \geq 25$	$109.22mb$	$113.56mb$
	$ADC\ count \geq 81$	$35.498mb$	$36.510mb$
	$81 \geq ADC\ count \geq 123$	$18.203mb$	$18.422mb$
C_{ADC}	$ADC\ count \geq 46$	1.00361	1.00361
	$ADC\ count \geq 25$	1.00354	1.00354
	$ADC\ count \geq 81$	1.00174	1.00174
	$81 \geq ADC\ count \geq 123$	0.99639	0.99639

Table 2.

Having photon positions reconstructed, the beam tilt and divergence is estimated and the geometrical acceptance A is calculated using the formula :

$$A = A_0(t_x, t_y) + B * (s_x - 2.1) \tag{11}$$

where $t_x,\ t_y$ are the beam tilts in x and y in $mrad$ and s_x is the dispersion of the photon position distribution in cm as seen by the position detector.The coefficients A_0, B are interpolated from Table 3.

$t_x[mrad]$	$t_y[mrad]$	A_0	B	$t_x[mrad]$	$t_y[mrad]$	A_0	B
−0.350	−0.150	0.90555	−0.10930	−0.100	0.000	0.97304	−0.07917
−0.300	−0.150	0.94093	−0.09911	−0.050	0.000	0.95681	−0.08966
−0.250	−0.150	0.96322	−0.08821	0.000	0.000	0.92965	−0.10251
−0.200	−0.150	0.97503	−0.07797	0.050	0.000	0.88794	−0.11047
−0.150	−0.150	0.97798	−0.08058	−0.350	0.050	0.90779	−0.10677
−0.100	−0.150	0.97036	−0.08158	−0.300	0.050	0.94276	−0.09465
−0.050	−0.150	0.95374	−0.09097	−0.250	0.050	0.96472	−0.08181
0.000	−0.150	0.92493	−0.10752	−0.200	0.050	0.97682	−0.07682
0.050	−0.150	0.87997	−0.10822	−0.150	0.050	0.97912	−0.07657
−0.350	−0.100	0.90848	−0.10975	−0.100	0.050	0.97240	−0.07903
−0.300	−0.100	0.94265	−0.09745	−0.050	0.050	0.95642	−0.09128
−0.250	−0.100	0.96535	−0.08527	0.000	0.050	0.92839	−0.10118
−0.200	−0.100	0.97673	−0.07743	0.050	0.050	0.88718	−0.10888
−0.150	−0.100	0.97917	−0.07560	−0.350	0.100	0.90384	−0.11656
−0.100	−0.100	0.97306	−0.08338	−0.300	0.100	0.93979	−0.10286
−0.050	−0.100	0.95655	−0.08899	−0.250	0.100	0.96226	−0.08665
0.000	−0.100	0.92860	−0.10280	−0.200	0.100	0.97435	−0.07974
0.050	−0.100	0.88732	−0.11154	−0.150	0.100	0.97675	−0.08019
−0.350	−0.050	0.90926	−0.11013	−0.100	0.100	0.96951	−0.08342
−0.300	−0.050	0.94342	−0.09671	−0.050	0.100	0.95278	−0.09334
−0.250	−0.050	0.96581	−0.08630	0.000	0.100	0.92463	−0.10503
−0.200	−0.050	0.97732	−0.07737	0.050	0.100	0.88235	−0.11298
−0.150	−0.050	0.97921	−0.07275	−0.350	0.150	0.88535	−0.11444
−0.100	−0.050	0.97287	−0.07780	−0.300	0.150	0.92715	−0.10793
−0.050	−0.050	0.95685	−0.08787	−0.250	0.150	0.95357	−0.09945
0.000	−0.050	0.92985	−0.10289	−0.200	0.150	0.96606	−0.08899
0.050	−0.050	0.88867	−0.11363	−0.150	0.150	0.96838	−0.08800
−0.350	0.000	0.90841	−0.10583	−0.100	0.150	0.96043	−0.09611
−0.300	0.000	0.94394	−0.09908	−0.050	0.150	0.94065	−0.10255
−0.250	0.000	0.96568	−0.08512	0.000	0.150	0.90858	−0.10956
−0.200	0.000	0.97766	−0.07853	0.050	0.150	0.86286	−0.10939
−0.150	0.000	0.97959	−0.07465	−−	−−	−−	−−

Table 3.

6 Bremstrahlung Rates

In the offline luminosity calculation the rates of 4 scalers with different energy cuts (triggers) are used. In this note the rates, as well as the luminosities obtained from these rates, are identified by the subscript in the following way:

$$\begin{array}{lcc} 2 & -- & E_\gamma \geq 2GeV \\ 5 & -- & E_\gamma \geq 5GeV \\ 10 & -- & E_\gamma \geq 10GeV \\ 10-16 & -- & 10GeV \geq E_\gamma \geq 16GeV \end{array}$$

The choice of the cuts is optimized in such a way that:

- R_{10-16} is the least sensitive to the variation of the calorimeter parameters, so L_{10-16} is measured with the least systematic error;
- R_5 is the least influenced by the pile-up effect;
- R_{10} is the most sensitive to the variation of the calorimeter parameters;
- R_2 is the most influenced by the beam size effect.

To obtain a clean bremsstrahlung rates for the colliding bunches, the measured rates have to be corrected for the background processes and the pile-up effect. The correction procedure is described in the next subsections.

6.1 Pile-up effect

The amount of the multiple photon events in the sample depends on the average number of bremsstrahlung photons per bunch crossing. This number is not constant during the running period, therefore the amount of multiple photon events is correlated with the rate of events counted by the scaler 10 GeV $< E_\gamma <$ 16 GeV.

The rates are corrected for multiple events using formula:

$$R'_i = R_i(1 + a_i R_{10-16}/N_{coll}) \tag{12}$$

where R'_i is the corrected rate for trigger i, R_i is the corresponding uncorrected rate, N_{coll} is the total number of colliding ep bunches. Coefficients a_i are obtained from Monte Carlo simulation assuming that higher order terms can be neglected. They are shown in Table 4 for the both running periods.

	1997	1998 − 1999
a_2	$5.209 * 10^{-5}$	$5.182 * 10^{-5}$
a_5	$1.071 * 10^{-5}$	$1.124 * 10^{-5}$
a_{10}	$-2.786 * 10^{-5}$	$-2.969 * 10^{-5}$
a_{10-16}	$2.125 * 10^{-5}$	$1.874 * 10^{-5}$

Table 4

The effect of (12) is demonstrated in fig.5. The relative differences between L_5 and the luminosities from other triggers before and after correction are shown as the function of the event rate for both running periods. The relative difference of uncorrected luminosities clearly depends on the event rate. After applying the correction this dependence almost disappears.

6.2 $e - gas$ contamination

The contamination of the total photon rate by $e - gas$ bremsstrahlung is estimated assuming that the contribution from $e-gas$ events scales with the electron current. The ep bremsstrahlung rate is calculated wtih the following formula:

$$R_i^{ep} = R_i - kR_i^{pilot} \tag{13}$$

where R_i^{pilot} is the $e - gas$ event rate measured using the electron pilot bunches and the factor $k = I_e^{coll}/I_e^{pilot}$ is the ratio of the total electron current in colliding bunches to that in the pilot bunches.

The contribution of the ep events in the total rate should depend on average on the proton beam current. Therefore this correction is demonstrated by plotting the average $< R_i^{ep}/R_i >$ versus proton current and the expected behaviour is observed (fig 6).

7 Systematic errors

The accuracy of the observed cross sections determination is limited by the errors in calculation of the theoretical cross section, the error of the geometrical photon acceptance estimation and the uncertainty of the calorimeter response parametrization. The ep bremsstrahlung photon rate uncertainty is due to $e - gas$ background subtraction and pile-up effect correction errors.

The contributon of different error sources to the total error is summarized in Table 5.

	$\Delta L_2/L$	$\Delta L_5/L$	$\Delta L_{10}/L$	$\Delta L_{10-16}/L$
acceptance error	0.8%	0.8%	0.8%	0.8%
cross section calculation	1.2%	0.6%	0.4%	0.5%
$e - gas$ *background subtraction*	0.1%	0.1%	0.1%	0.1%
multiple events correction	0.15%	0.15%	0.1%	0.4%
calorimeter response error	1.19%	1.11%	1.25%	0.93%
total	1.88%	1.51%	1.55%	1.34%

Table 5

The above values are found in the following way:

theoretical cross section uncertainty The Bethe Heitler formula assumes the electron bremsstrahlung in the Coulomb field of proton. Calculations also at the Born level but taking into account the proton spin and its structure, as well as the effects of proton recoil [7-9] , taking into account Z bozon exchange [8] and introducing the higher order correction may alter the Bethe Heitler cross section by 0.3%. Much less accurate is the knowledge of the beam size effect. In the present calculations the effect itself is -1.9%, -0.83%, -0.30% and -0.53% for L_2, L_5, L_{10}, and L_{10-16} respectively. Uncertainty of these corrections is about 50% of their values.

acceptance error The acceptance error was obtained by varying the shape of the acceptance contour within allowed range and varying the beam divergence by 0.01 $mrad$ to take into account the inaccuracies of the position determination.

calorimeter response error This error includes the uncertainty of the time independend parameters E_f, f_{nl} and σ_0 as well as the changing in time values of the pedestals and the gain. For constant calorimeter parameters it was estimated as the maximum variation of the observed cross sections within the optimum parameter ranges determined by fit. Additionally the error coming from the uncertainty of the smearing function was estimated by changing parameter α in (5). (With increasing α the smearing function approaches the gaussian distribution) The calibration constant may be additionaly biased due to some pile-up effect for electron pilot bunches (as in the 12 GeV test sample). Uncertainty in pedestal determination was evaluated from the spread of the pedestal values as ± 0.03 $ADC\ counts$ measured for different colliding bunches, and from the uncertainty of knowledge of the real position of the ADC bin.

The contributions to the calorimeter response error are summarized in Table 6. The change of proton beam energy from 820 GeV to 920 GeV has no influence on these errors. The total error is obtained by adding all contribution in quadrature.

	$\Delta L_2/L$	$\Delta L_5/L$	$\Delta L_{10}/L$	$\Delta L_{10-16}/L$
E_f, σ_0, f_{nl}	1.10%	1.01%	1.10%	0.90%
α	0.39%	0.31%	0.32%	0.22%
c_γ	0.20%	0.34%	0.51%	0.08%
ADC_{ped}	0.16%	0.10%	0.07%	0.07%
$total$	1.19%	1.11%	1.25%	0.93%

Table 6

$e - gas$ **background substraction** The error is estimated by observing deviations in rate to current ratios for electron pilot bunches. Systematic dependence of this ratio on the bunch crossing number is noticed but this deviation does not exceed 3% of the average value [4]. Since the amount of this background is small ($\simeq 2\%$) the systematic error from this source does not exceed 0.1%.

correction for the event pile-up Evaluation of the correction parameters (Table 4) is dependent on the treatment of the low energy photons (below E_f) for which the calorimeter response is not well parametrized. Therefore we accept as an error the half of the difference between two extreme simplifications :

- an additional photon of $E < E_f$ is fully absorbed in the filter;
- an additional photon of $E < E_f$ passes the filter

is taken.

8 Outlook

Only the error on the geometrical acceptance A affects all scalers equally. The other possible errors are different for different scalers. Therefore as a check the relative differences of the luminosities from different triggers are used:

$$\Delta L_{i,j}/L = (L_i - L_j)/L_5. \tag{14}$$

They are shown in fig.7 for the running period 1997 and in fig. 8 for 1998-1999. The very good agreement between L_{10-16} and L_5 is observed. L_2 and L_{10} are off by about 1%. The distributions of the differences are close to gaussian for the period 1997, for 1998-1999 their shape is strange. It is worth noting that this strange shape for some $\Delta L/L_5$ during 1998-1999 running period (a shoulder at the negative values) disappears when the requirement that the electron beam position is close to the nominal value was imposed (see Fig. 9). The good agreement for $e - gas$ luminosities indicates that the major sources of the luminosity error are connected with the theoretical cross section calculation for ep and the pile-up correction.

After correlating $\Delta L_{i,j}/L$ with various parameters of the collision following conclusion can be drawn:

- $\Delta L_{i,j}/L$ are correlated with the beam tilt. figs 10a and 10b show $< \Delta L_{i,j}/L >$ as the function of the average photon position in the position detector (the averaging is over the entries in the environmental record) . It seems that either the radiation damages are seen in the calorimeter scintilators or the averaging between the top and bottom readout of the scintilators is not quite correct. This effect showed up in the period 1998-1999 because of the larger beam spread than before. After selecting the records where the electron beam is close to its nominal tilt the distribution of $\Delta L_{i,j}/L$ becomes close to gaussian (fig. 10).

- $\Delta L_{i,j}/L$ are correlated with the specific luminosity. It can be explained by the beam size effect (depending on the parameters of the beam crossing area) which is underestimated. It also may be an evidence that pile-up effect are not properly treated. These correlations are shown on fig. 11.

Since $\Delta L_{i,j}/L$ for any contribution to the total error is less than $0.5\Delta L/L$ one can conclude looking at figs 8 and 10 that there are still the errors unaccounted for. The total systematic error for all scalers should be increased by 0.5%.

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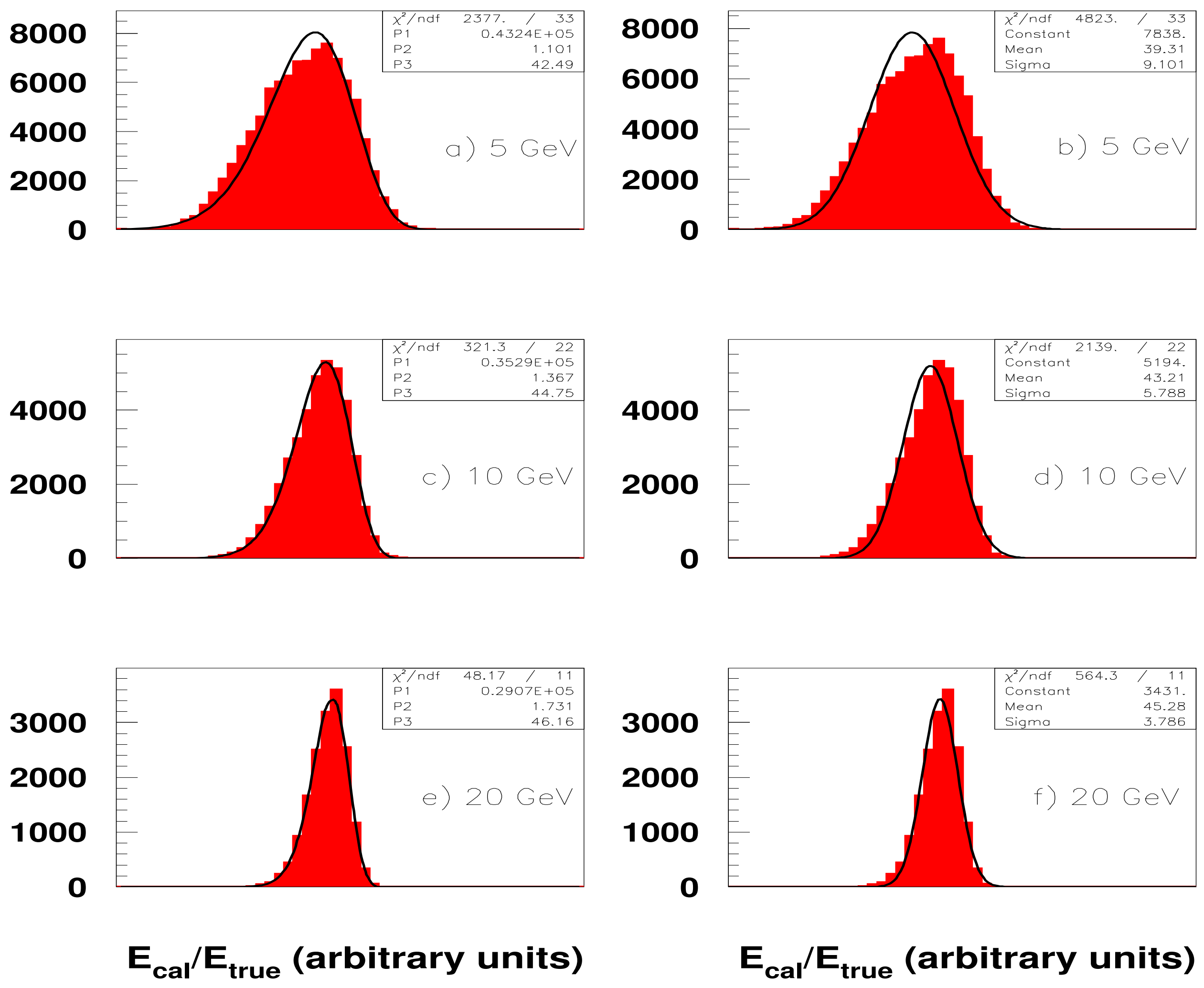

Figure 1: The EGS4 simulation of the calorimeter smearing for three different photon energies. On figs a), c), d), the result of the fit with the asymetric funcion is shown. On figs b), d), f) the result of the fit with gaussian distribution is shown.

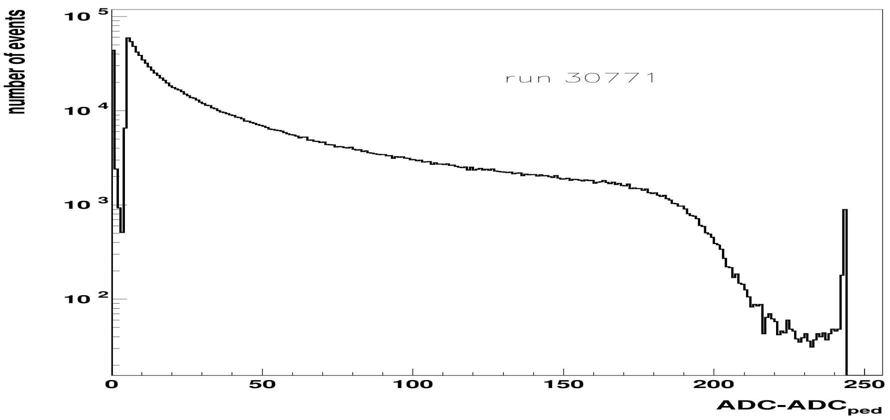

Figure 2: The ep bremsstrahlung photon spectrum for the typical run.

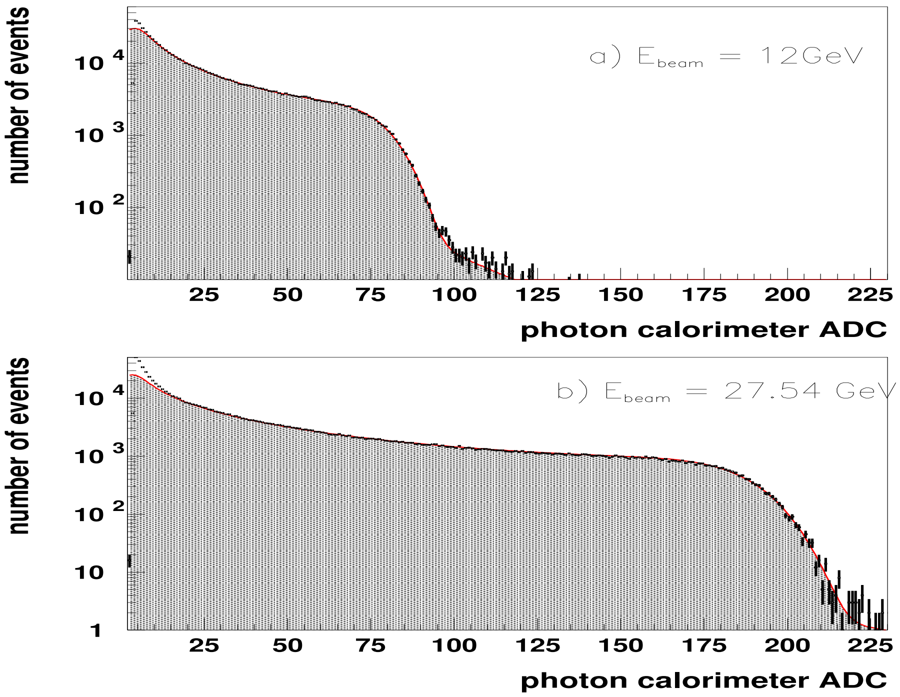

Figure 3: The $e - gas$ bremsstrahlung photon spectra for two electron beam energies. The points represent the data, the shaded histogram - the fitted function.

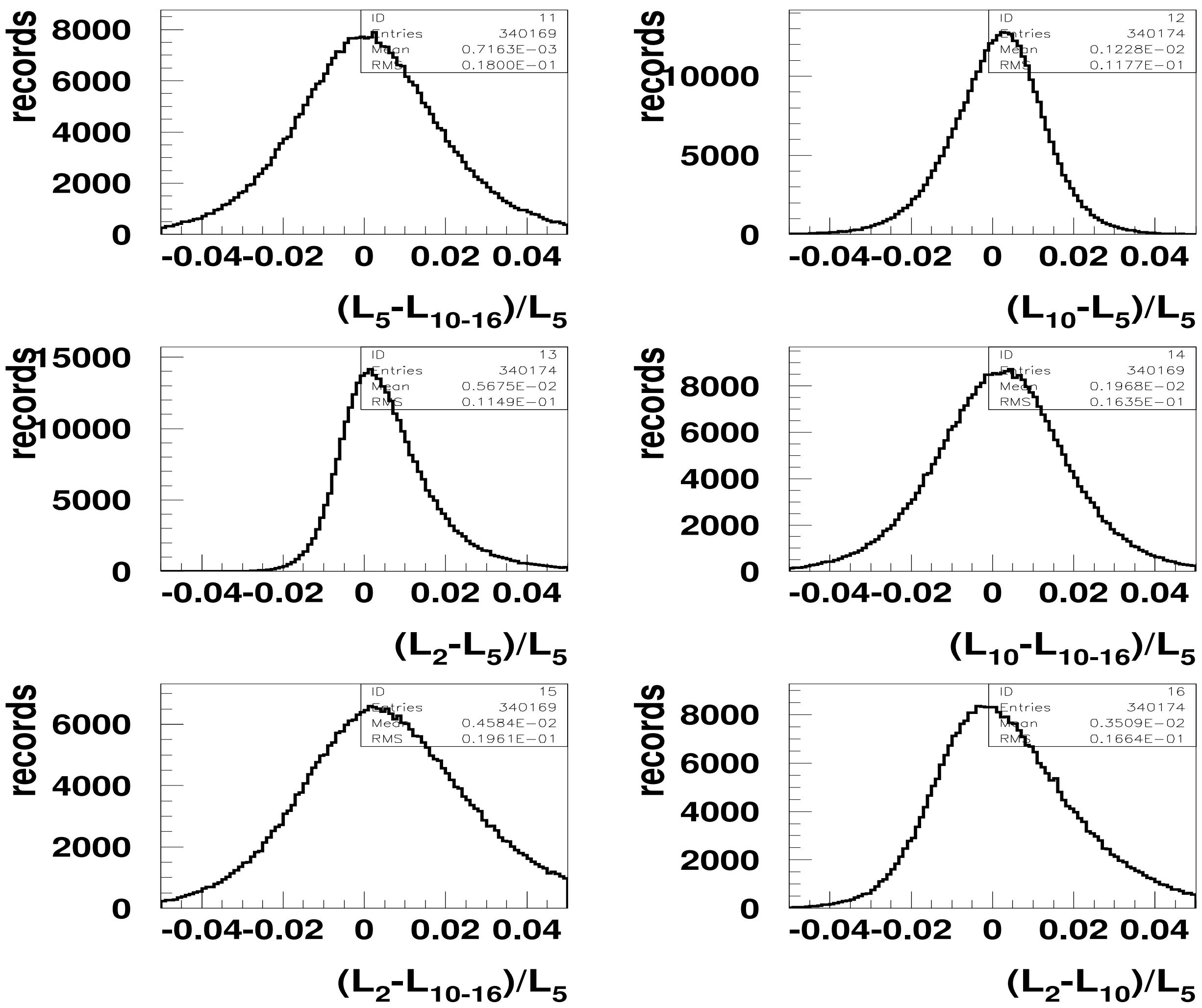

Figure 4: The relative differences for e-gas luminosities obtained with different triggers

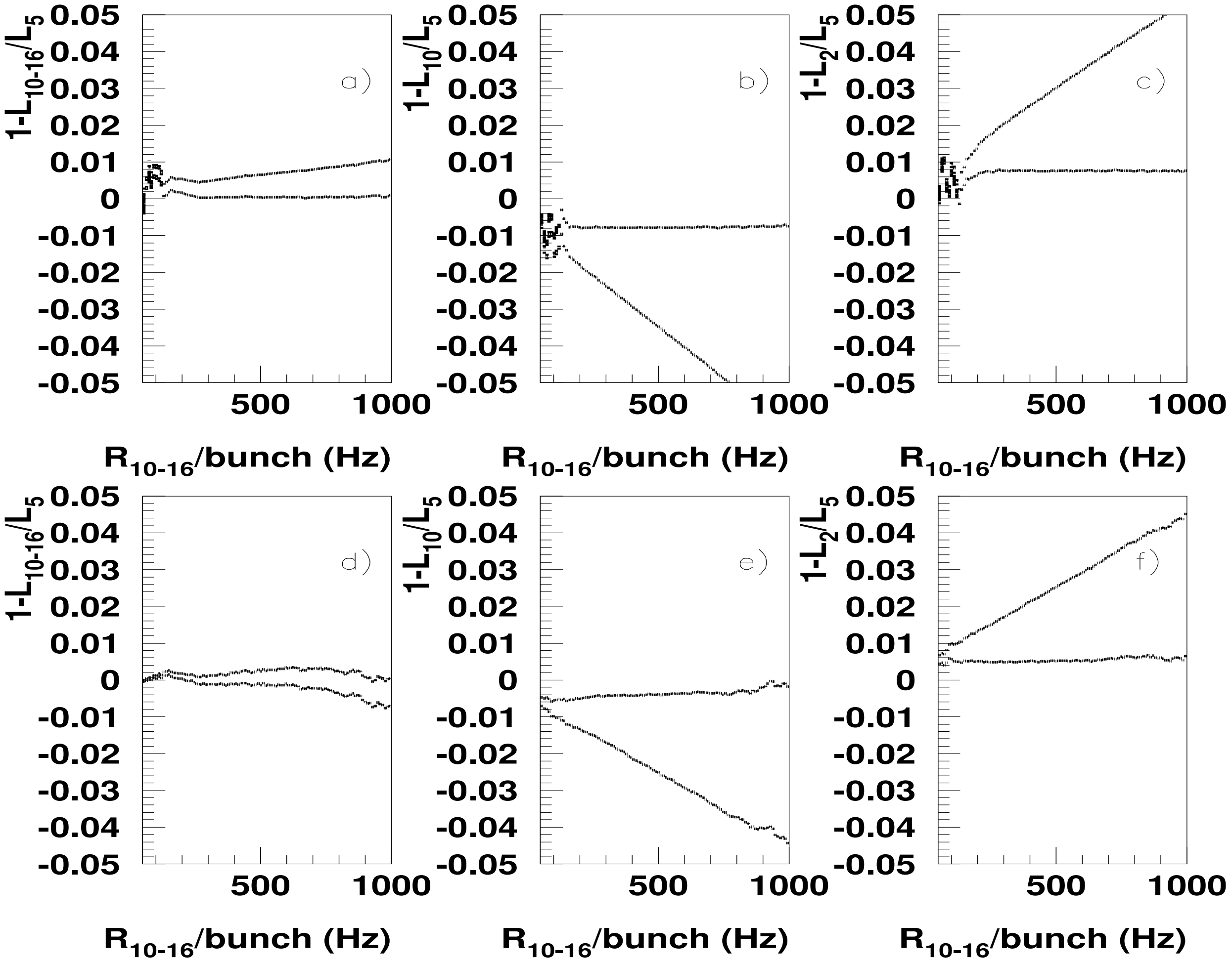

Figure 5: The relative differences for e-p luminosities obtained with different triggers versus the rates of events 10GeV-16GeV trigger, before and after the correction for the pile-up effect. For 1997 running period Figs. : a) -c) , for 1998-1999 Figs. d) - f).

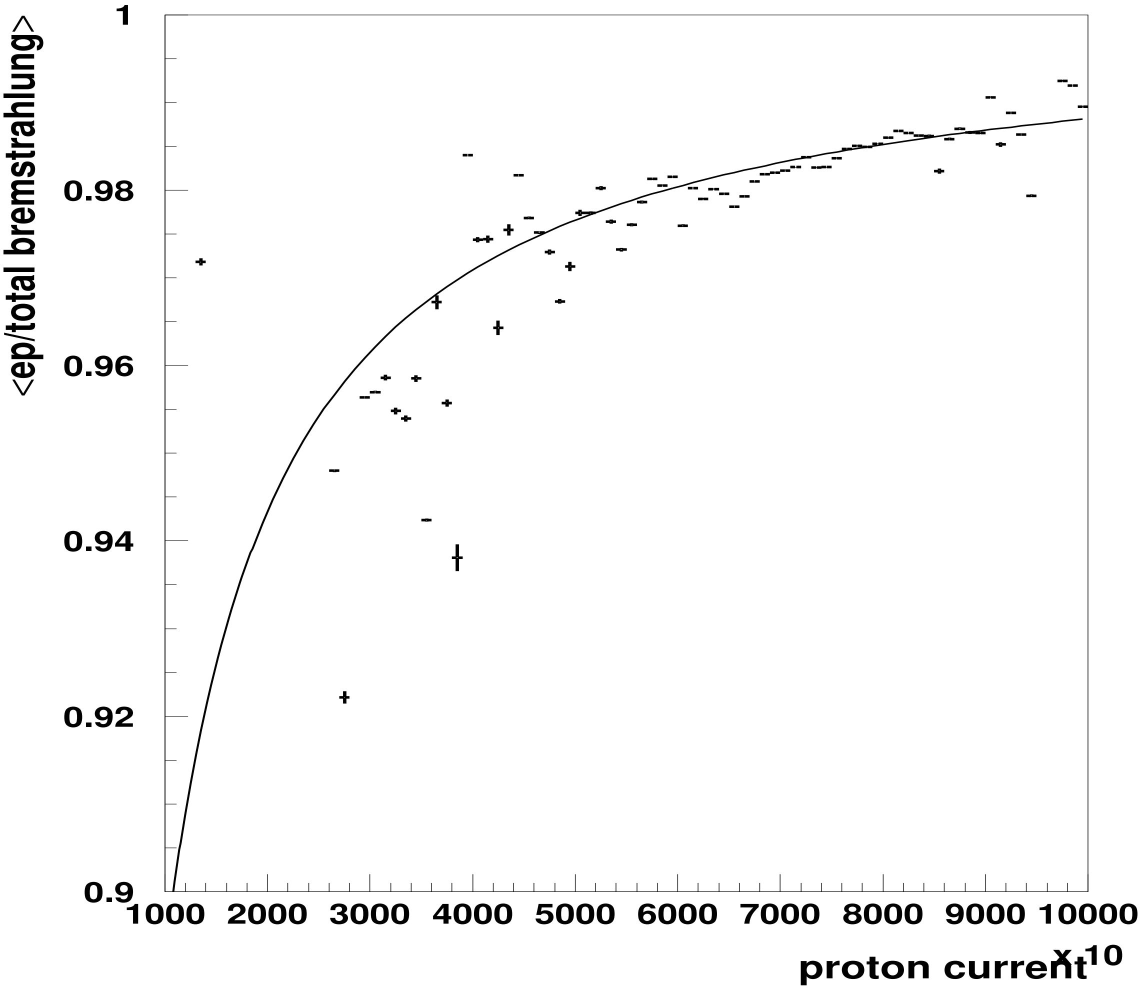

Figure 6: The average fraction of ep bremsstrahlung photons in the total rate versus proton current summed over all bunches. The curve represent expected tendency : x/(x+a)

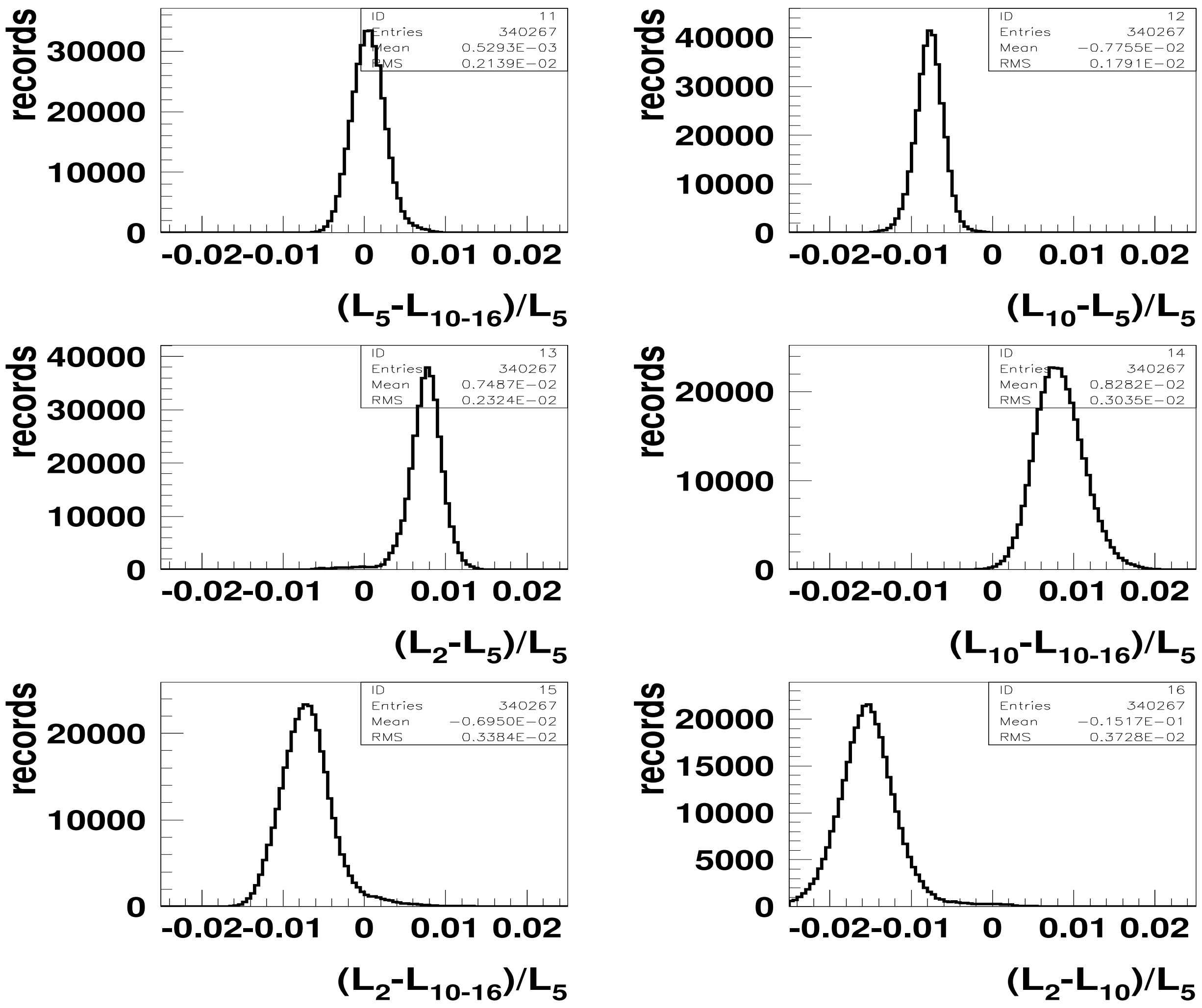

Figure 7: The distributions of relative differences for e-p luminosities obtained with different triggers for the running period 1997.

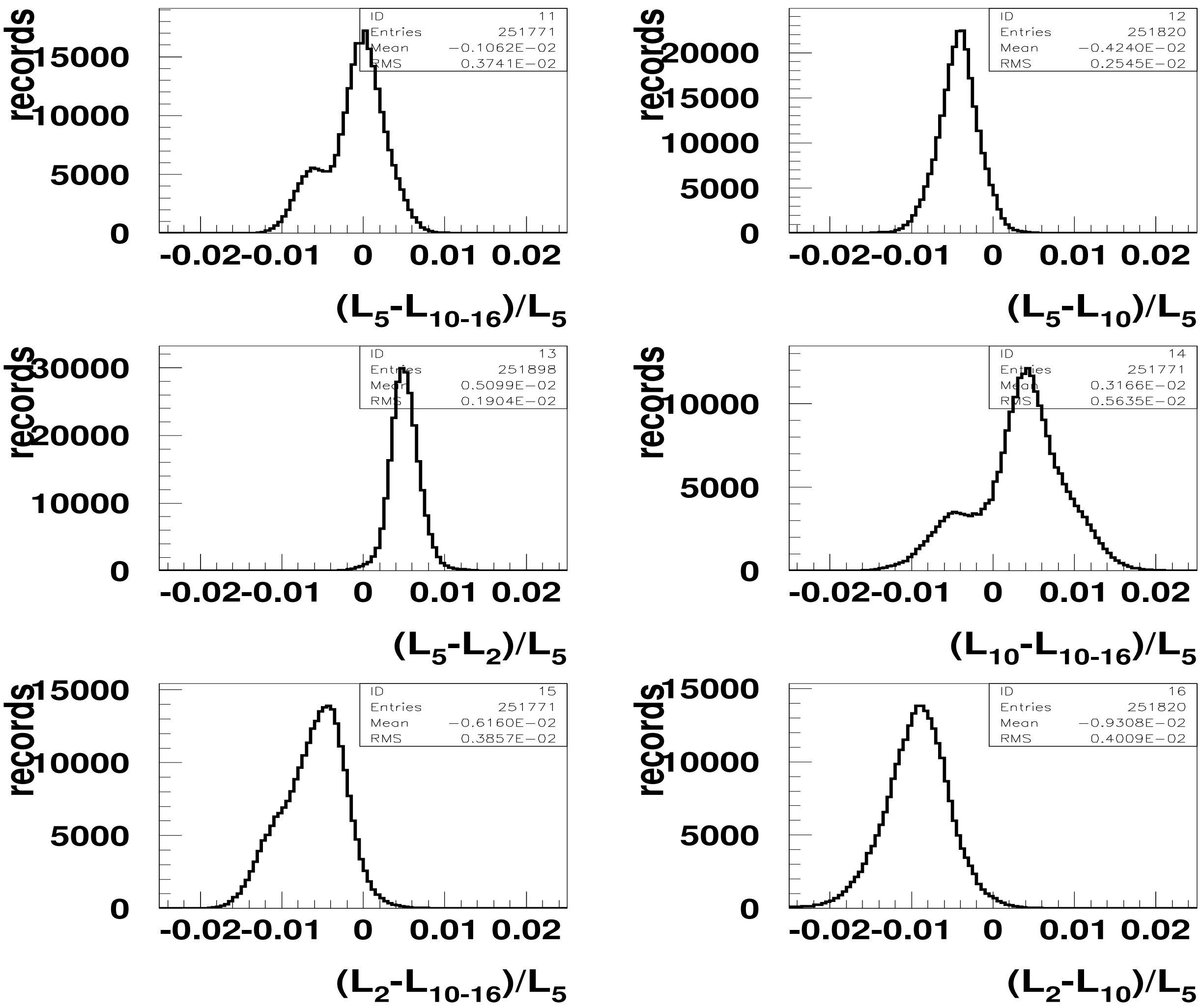

Figure 8: The distributions of relative differences for e-p luminosities obtained with different triggers for the running period 1998-99.

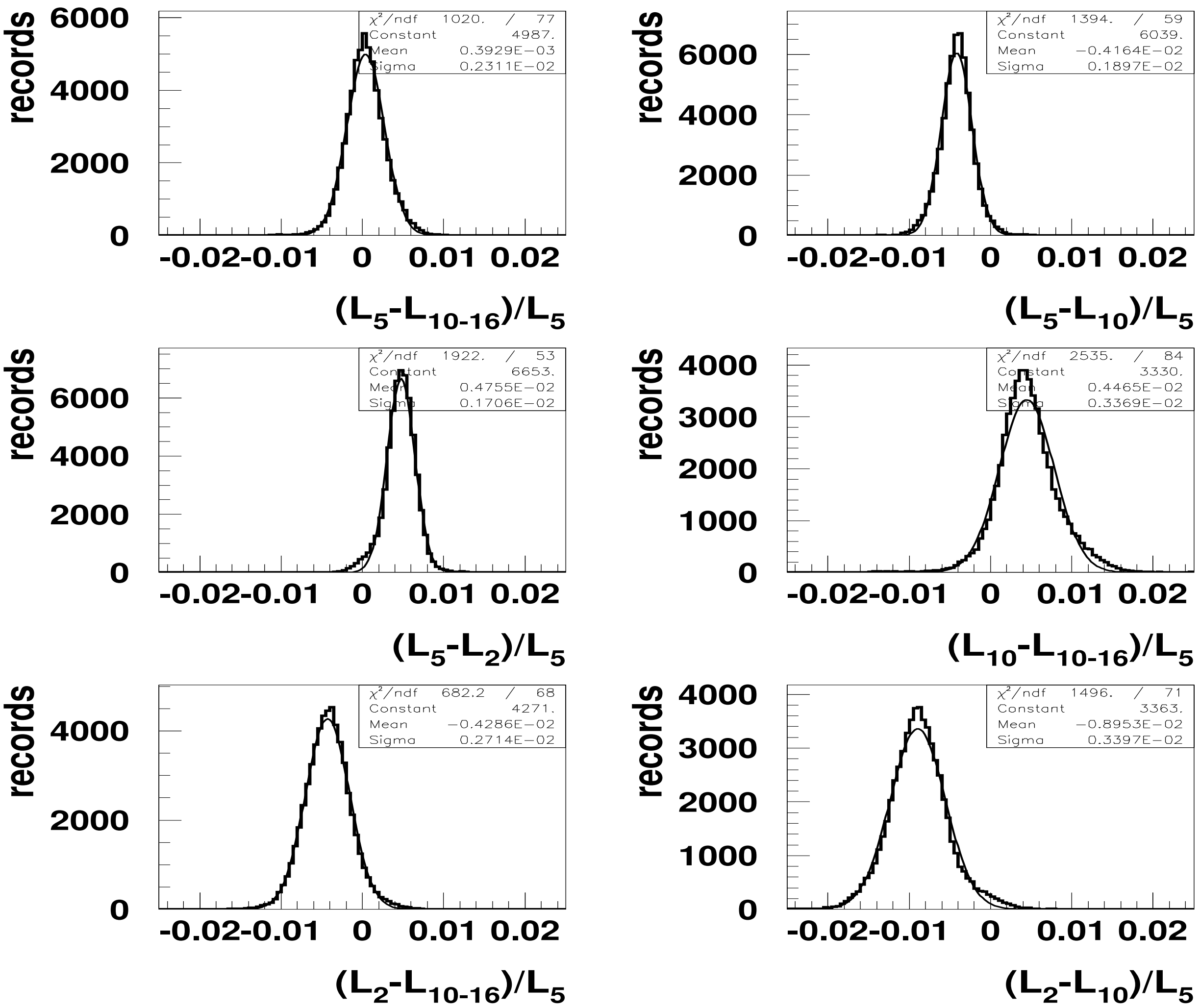

Figure 9: The distributions of relative differences for e-p luminosities obtained with different triggers for the running period 1998-99 and the environmental records taken when the electron beam position was close to nominal.

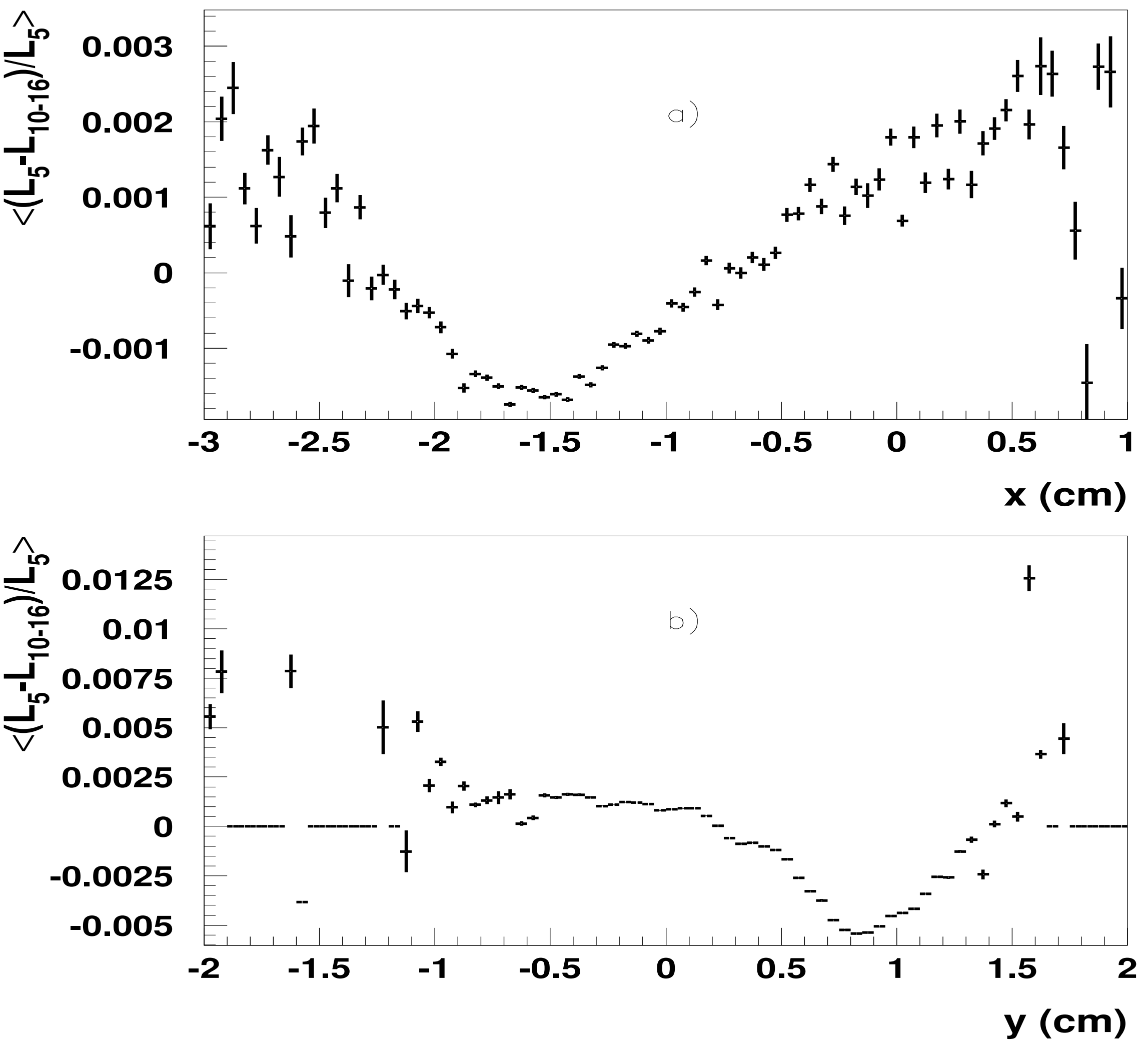

Figure 10: The average relative differences of the luminosity from two triggers versus photon position: a) horizontal, b) vertical for the running period 1998-1999.

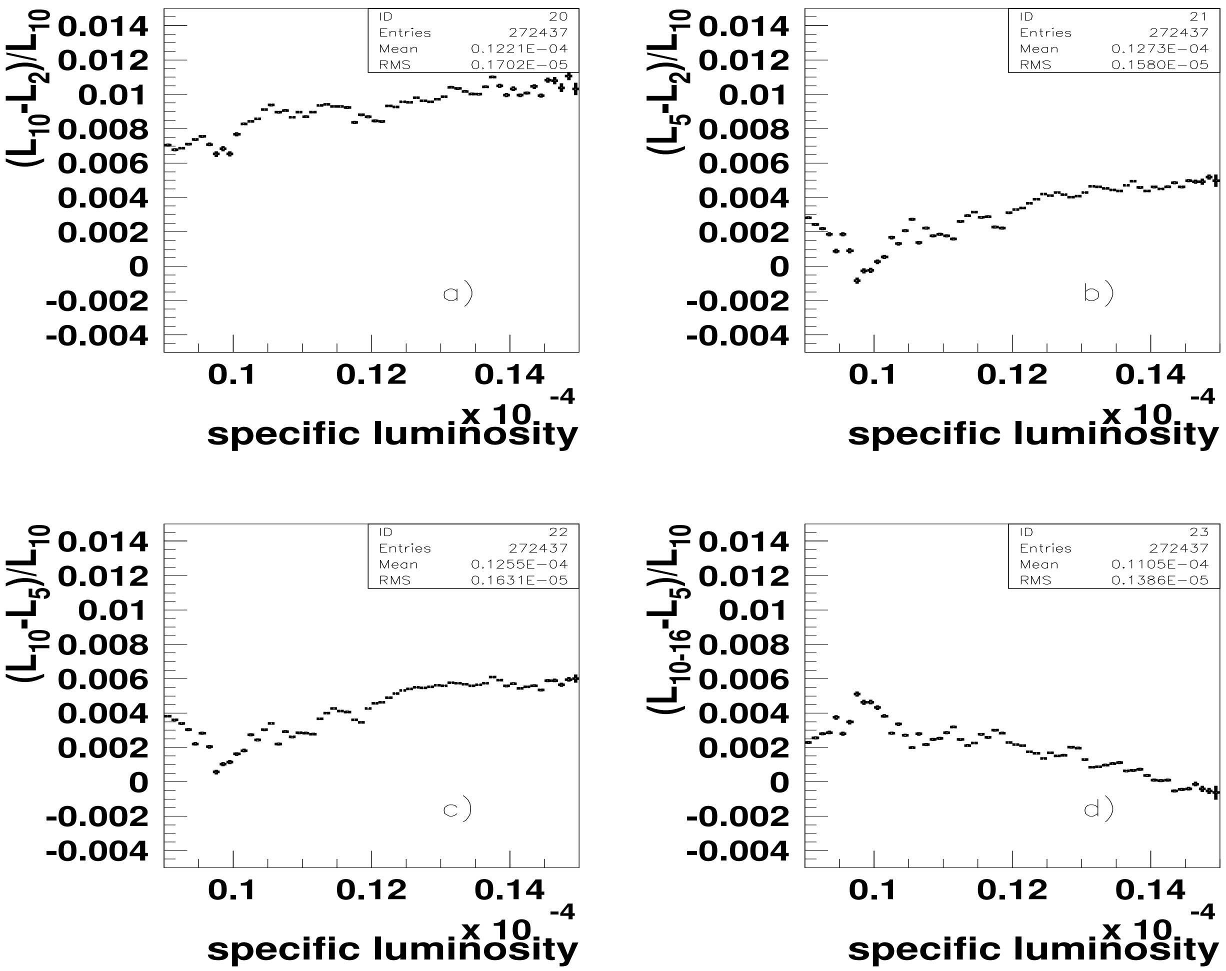

Figure 11: The average relative differences of e-p luminosities obtained with different triggers versus specific luminosity.