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Symmetric Møller/Bhabha luminosity monitor for the *OLYMPUS* experiment.

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Recent determinations of the proton electric to magnetic form factor ratio indicate an unexpected discrepancy between the ratio obtained using polarisation transfer measurements and the ratio from Rosenbluth separation technique in unpolarised cross section measurements. This discrepancy has been explained theoretically as the effect of two-photon exchange.

The *OLYMPUS* experiment at DESY proposed to measure the ratio of positron-proton and electron-proton elastic scattering cross sections. The experiment utilised beams of electrons and positrons in the DORIS ring at $2.0\,GeV$ incident on an unpolarized internal hydrogen gas target and the BLAST detector from the MIT-Bates Linear Accelerator Center with modest upgrades.

In order to reduce the systematic error from the determination of luminosity, redundant measurements of the relative luminosity were necessary. The symmetric Møller/Bhabha luminosity monitor built at the University of Mainz consisted of two symmetric arrays of lead fluoride (PbF_2) crystals. Results of the performance of the symmetric Møller/Bhabha luminosity monitor will be presented in this contribution.

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1. The proton electromagnetic form factors

Recent determinations of the proton electric to magnetic form factor ratio indicate an unexpected discrepancy between the ratio obtained using polarisation transfer measurements and the ratio from Rosenbluth separation technique in unpolarised cross section measurements. This discrepancy has been explained as the effect of multiple photon exchange beyond the usual one-photon exchange approximation in the calculation of the elastic electron-proton scattering cross section.

The elastic electromagnetic form factors of the proton have been explored extensively during the last 50 years. The form factors describe the internal structure of the proton. The electric form factor $G_E(Q^2)$ describes the spatial distribution of the charge and the magnetic form factor $G_M(Q^2)$ describes the magnetisation. The elastic electromagnetic form factors depend only on the four-momentum transfer squared Q^2. They have been determined using the Rosenbluth formula (Ref. [1]) in elastic e-p scattering:

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} \cdot \frac{1}{1+\tau}\left(G_M^2 + \frac{\varepsilon}{\tau}G_E^2\right) \tag{1.1}$$

where $\tau = Q^2/4M_P^2$, ε is the transverse virtual photon polarisation $\varepsilon = 1+2(1+\tau)\tan^2(\theta^2/2)^{-1}$, θ is the electron scattering angle in the laboratory frame and $(d\sigma/d\Omega)_{Mott}$ is the Mott differential cross section. It follows from this formula that the proton form factors can be determined by measuring the differential cross section at fixed momentum transfer Q^2, but with different electron scattering angles and incident beam energies, Ref. [2].

In the late 1990's, development of polarised beams, polarised targets and polarimeters gave the possibility to access the ratio of the form factors more directly through the interference of G_E and G_M in spin-dependent elastic cross section asymmetries, Refs. [3, 4]. In the Born approximation, the polarisation of the recoiling proton along its motion (P_l) is proportional to G_M^2 while the component perpendicular to the motion (P_t) is proportional to $G_E G_M$. Since it is much easier to measure ratios of polarisations, this method has been used mainly to determine the ratio G_E/G_M through a measurement of P_t/P_l using:

$$\frac{P_t}{P_l} = -\sqrt{\frac{2\varepsilon}{\tau(1+\varepsilon)}}\frac{G_E}{G_M}. \tag{1.2}$$

It came as a big surprise that the high precision polarisation transfer measurements at Jefferson Laboratory at higher momentum transfers gave striking evidence that the proton form factor ratio $\mu G_E/G_M$ was monotonically falling with Q^2. This Q^2 dependence was dramatically different from what was observed with the unpolarised Rosenbluth method, Ref. [5].

The generally accepted explanation for the discrepancy between the recoil polarization and Rosenbluth determinations of the elastic proton form factor ratio is the exchange of multiple photons during the electron-proton elastic scattering process. The goal of *OLYMPUS* is to determine the two photons exchange amplitude to the elastic scattering cross section. This contribution can be accessed through the cross section ratio of positron over electron elastic scattering on the proton:

$$\mathscr{R} = \frac{\sigma(e^+p)}{\sigma(e^-p)} = 1 + \alpha \frac{4\Re(M_{1\gamma}^{\dagger} M_{2\gamma})}{|M_{1\gamma}|^2} + \cdots \tag{1.3}$$

2. The Olympus Experiment

The OLYMPUS experiment make use of the DORIS 2.01 GeV electron and positron beam at DORIS. The OLYMPUS experiment takes advantage of the BLAST detector which was successfully operated at the MIT-Bates Linear Accelerator Center, see Ref. [6]. The detector was based upon an eight sector, toroidal, magnetic field. The two horizontal sectors from $20° < \theta < 80°$ and $-15° < \phi < 15°$ were instrumented with detector components while the two vertical sectors were used by the internal targets and the vacuum system for the beamline.

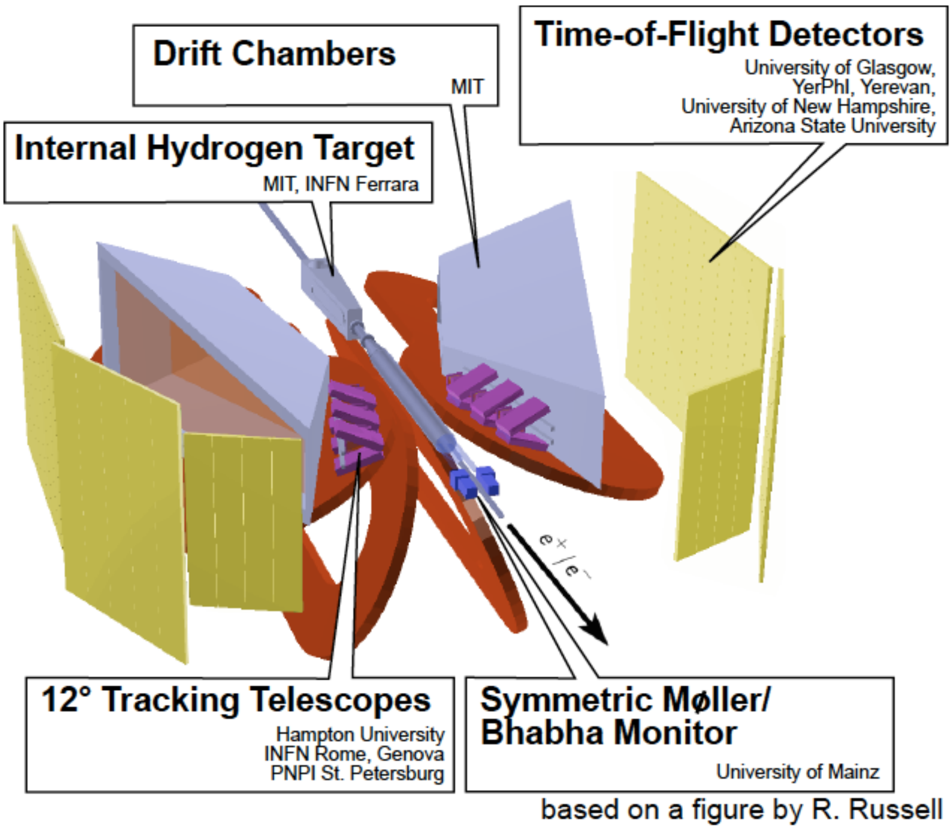

Figure 1: Schematic of the OLYMPUS detector showing the main detector elements.

The detector components in the horizontal sectors are the BLAST wire chambers and time of flight scintillators. As such the detector is left/right symmetric. For a DORIS beam energy of 2.010 GeV, it covered a kinematic region for a transverse virtual photon polarization between $0.37 < \varepsilon < 0.9$ with a four-momentum transfer squared in the range $0.6 < Q^2 < 2.2\,\mathrm{GeV}^2/\mathrm{c}^2$.

In addition to the toroid magnet, wire chambers and time of flight scintillators from the BLAST detector, some new detector components were built to improve performance and address the requirements of the OLYMPUS experiment. Specifically a set of small detectors at forward angles were built to monitor the luminosity of the experiment during running, Ref. [7]. This is important for normalising the statistics obtained for the different combinations of electron/positron beams and magnet polarity. A simple schematic view of the OLYMPUS detector configuration is shown in Fig. 1.

3. Symmetric Møller/Bhabha Luminosity Monitor

The symmetric Møller/Bhabha luminosity detector (SYMB) was built in Mainz and consists of two symmetric arrays of lead fluoride (PbF_2) crystals at small scattering angles (1.2°), integrated on the OLYMPUS geometry. The detector is placed inside two μ-metal boxes to shield the photomultiplier tubes (PMT) and the electronics components from the strong magnetic field.

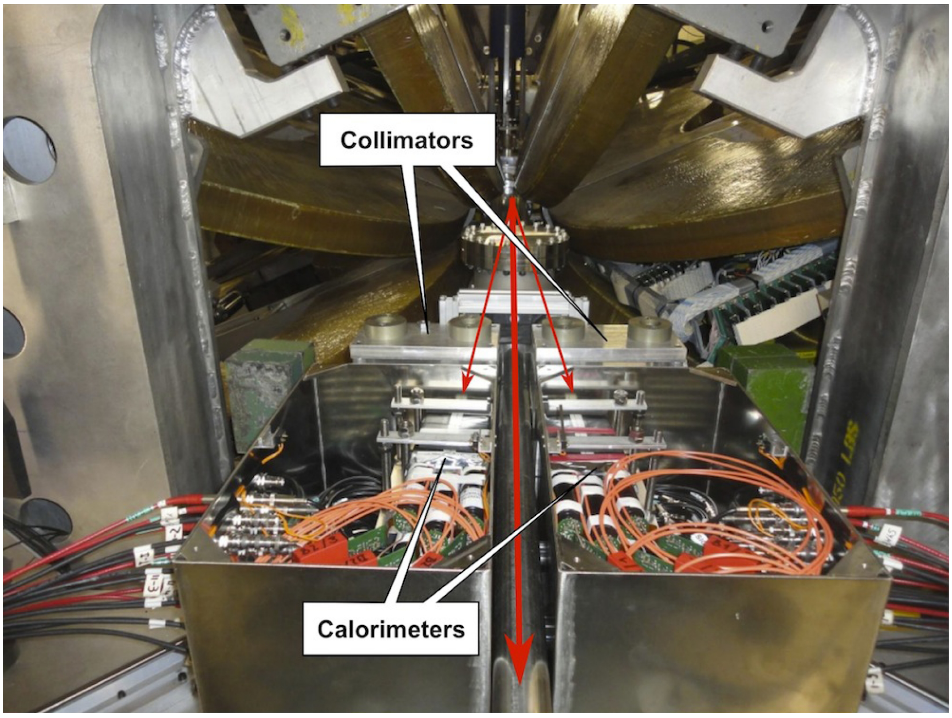

Figure 2: View of the Symmetric Møller/Bhabha luminosity detector over its support table. Accurate rail systems and a collimator are placed in front of the μ-metal box.

On Fig. 2, we can see the final accommodation of the SYMB detector within the OLYMPUS experiment. The 3×3 array of lead fluoride crystals with the PMTs, signal cables, high voltage (HV) cables and quartz fibres for the gain monitor system are located inside the μ-metal boxes.

The Bremsstrahlung around the beam pipe forced us to shield the front part of our detector with a collimator of lead bricks, and move out our detector with one accurate rail system. A number of Monte Carlo simulation studies were done on the Bremsstrahlung background for the optimization of the collimator. Different cuts in the energy spectrum were applied to extract the luminosity signal.

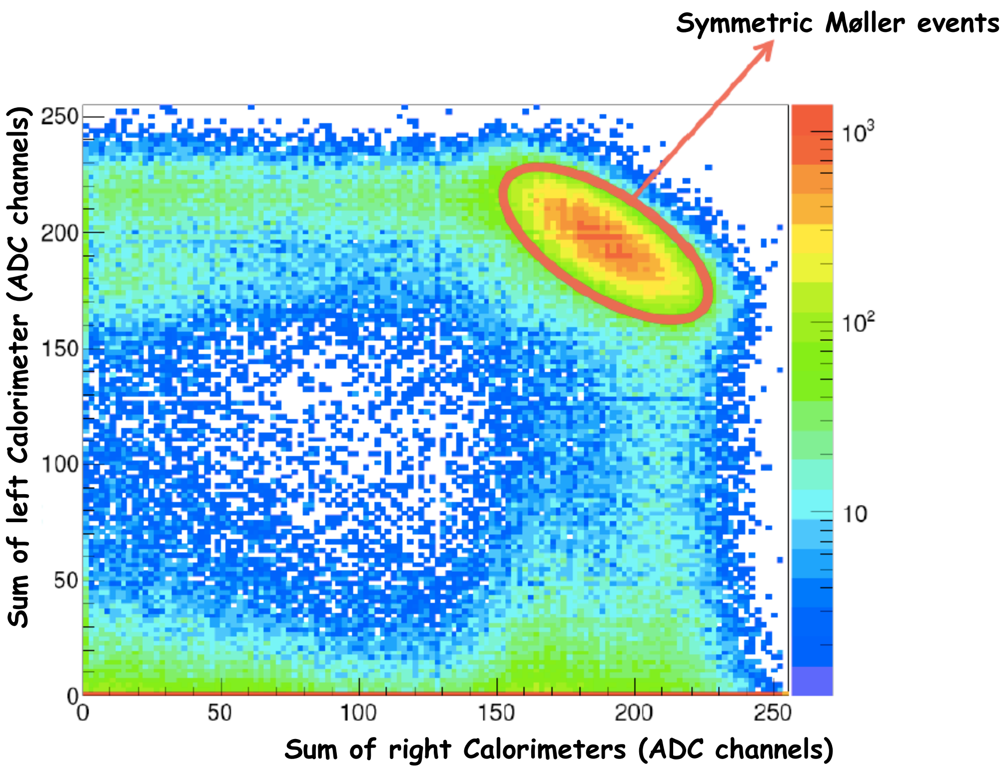

Figure 3: 2D energy spectrum of the Møller events from the coincidence of the two calorimeters. The data were taken with the fully commissioned symmetric Møller/Bhabha luminosity detector.

The SYMB data were taken in left/right coincidence mode. The Fig 3 shows the sum of the energy (in ADC channels) deposited in the left crystal array versus the right array. We can see on the top right of the 2D histogram the symmetric Møller events. The horizontal line and the vertical line on the 2D histogram are random coincidence events and background.

Luminosity $\mathscr{L}$ is the ratio of the measured scattering rate $\mathscr{R}$ and the effective cross section σ of the scattering reaction.

$$\mathscr{L} = \frac{\mathscr{R}}{\sigma} \tag{3.1}$$

The number of counts per SYMB readout depends on the target flow, beam current, beam position and slope, etc. As a first check of SYMB the measured rate was compared to the expected one. The rate $\mathscr{R}$ shown in Fig. 4 is the rate measured by the SYMB normalized to the dead time corrected slow control luminosity and multiplied by the design luminosity $\mathscr{L}_{nominal} = 2 \cdot 10^{33} cm^{-2} s^{-1}$.

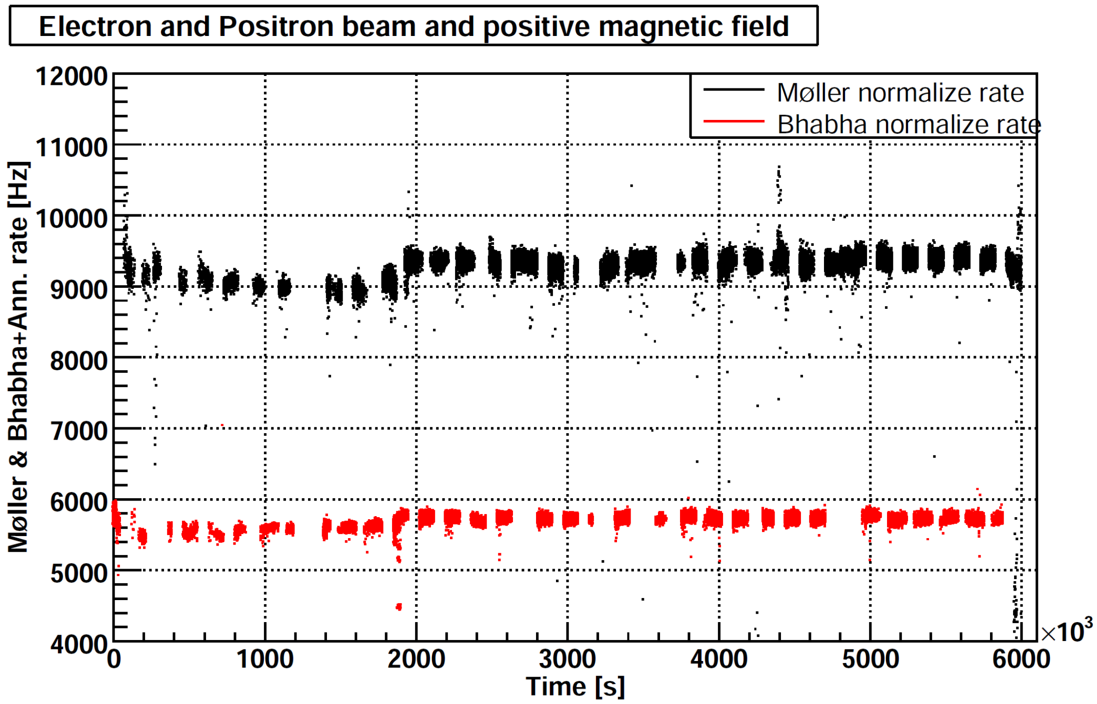

Figure 4: Normalized rate for Møller in black and for Bhabha plus Annihilation in red, collected between two SYMB readouts.

The effective angular acceptance of the SYMB strongly depends on the beam conditions (i.e. beam position and angle of incidence on the target). This impacts the measured cross section σ of the Møller, Bhabha and Annihilation processes. The fluctuations on the normalized rate shown in Fig. 4 can be explained by this dependency. In Fig. 5 the dependence of the normalized rate due to the horizontal beam position scan is shown.

The measured rates during the normal running conditions correspond to the expected rates estimated by our Monte Carlo simulation and the different luminosity detectors agree in $\sim 1\%$ with each other. Our next step is the acceptance correction for systematics effects to reduse the error on

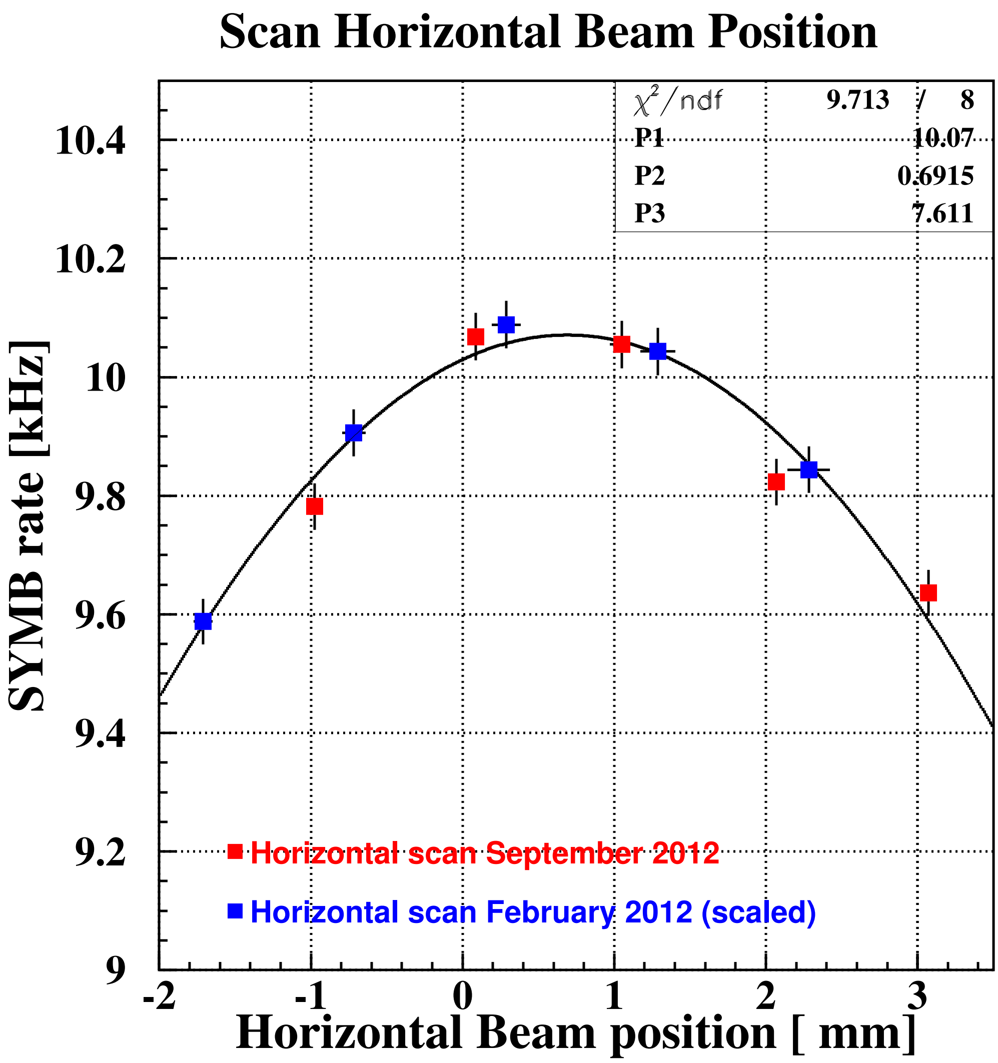

Figure 5: Normalized Møller rates for a horizontal electron beam scan. The data from February were scaled due to the difference on the gas target between the two data periods.

the final measurement of the ratio of positron-proton and electron-proton elastic scattering cross sections. Therefore, the ratio of luminosities is neither constrained to be constant nor to expected to be unity. With the goal of 1% systematic uncertainty on the ratio of differential cross sections, the ratio of luminosities needs to be measured to even higher precision ($\ll 1\%$).

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