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Feasibility Study of Deeply Virtual Compton Scattering using COMPASS at CERN

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Abstract. This paper presents the reactions which can be performed at COMPASS to study the Generalized Parton Distributions (GPDs). The high energy muon beam at CERN allows to measure Hard Exclusive Meson Production or Deeply Virtual Compton Scattering (DVCS) in the Bjorken regime in a large range of Q^2 and x_{Bj} (1.5 $\leq Q^2 \leq$ 7.5 GeV^2 and 0.03 $\leq x_{Bj} \leq$ 0.25). Exploratory measurements dedicated to ρ^0 or π^0 production can be investigated with the present setup. DVCS measurement require an upgrade of the COMPASS setup.

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1 Goal of an experiment with the high energy muon beam

In the quest for understanding the structure of the nucleon, Generalized Parton Distributions (GPDs) [1,2] have emerged as a very promising tool. They provide a unified description of the nucleon by interpolating between the parton distributions and the hadronic form factors. Moreover GPDs complete the nucleon puzzle as they give a measurement of total angular momentum contribution of the quarks to the nucleon spin. Experimentally the GPDs can be accessed in exclusive measurements such as Hard Exclusive Meson (ρ, π...) Production (HEMP) and Deeply Virtual Compton Scattering (DVCS). The latter reaction is the simplest from the theoretical point of view but also the most difficult experimentally because one has to select perfectly the final state (one lepton, one proton and one photon) among all the possible reactions. In pratice Meson Production can be investigated with the present COMPASS setup at CERN while a DVCS measurement at COMPASS would require an upgrade of the existing apparatus.

Experiments have already been undertaken at very high energy with the HERA collider [3,4] to study mainly the gluon GPDs at very small x_{Bj} ($\leq 10^{-2}$). Larger values of x_{Bj} have been investigated in fixed target experiments at JLab [5] (at 6 GeV, with plans for an upgrade at 11 GeV) and HERMES [6] (at 27 GeV). The experimental program using COMPASS at CERN (at 100 and/or 190 GeV) would enlarge the kinematical domain to a large range of Q^2 and x_{Bj} (1.5 $\leq Q^2 \leq$ 7 GeV^2 and 0.03 $\leq x_{Bj} \leq$ 0.25) (see Fig. 1). A large range in Q^2 is required to control the factorisation in a hard, pertubatively calculable amplitude and a soft amplitude which is parametrized by the generalized parton distributions $H, E, \tilde{H}, \tilde{E}$. The GPDs depend on three kinematical variables: x and ξ parameterize the longitudinal momentum fractions of the partons, while t relates to the transverse momentum transfer.

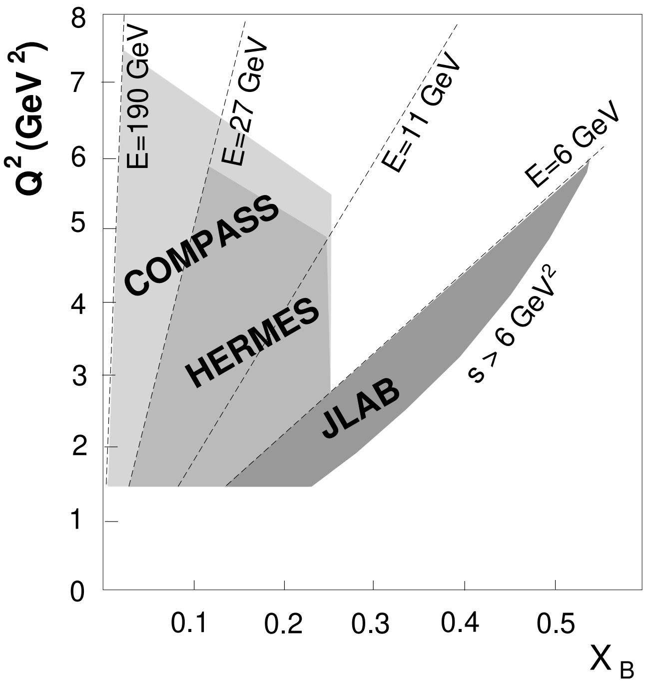

Fig. 1. Kinematical coverage for various planned or proposed experiments. The limit $s \geq 6$ GeV^2 assures to be above the resonance domain, and $Q^2 > 1.5$ GeV^2 allows to reach the Deep Inelastic regime.

Since the theoretical proof of factorization assumes that the transfer t is finite (that is $t/Q^2 \to 0$) [7], we consider in the following $|t|$ smaller than 1 GeV^2. Another condition of factorization concerns the helicity of the virtual photon. In case of Hard Exclusive Meson Production it is mandatory to impose that the virtual photon be longitudinal in order to select the perturbative gluon exchange. Experimentally we should consider

Rosenbluth separation for π^0 production, while for ρ^0 production we can select longitudinal ρ^0s through the angular distribution of the decay products and assume the s-channel helecity conservation. Hard Exclusive Meson Productions seem more complex to analyze as they contain non perturbative information on both the target and the produced meson. Nevertheless they offer the possibility to disentangle different GPDs (vector meson production depends on H and E only; pseudo-scalar production depends on $\tilde{H}$ and $\tilde{E}$ only) and to separate contributions from different flavors. Forward differential longitudinal ρ^0_L electroproduction cross section measurements which provide the largest counting rates, have already been undertaken and are presented in Fig. 2 as a function of c.m. energy W for three values of Q^2 (5.6, 9 and 27 GeV^2). The theoretical curve is an incoherent sum of the quark and gluon contributions [8]. No measurement have been done at x_{Bj} larger than 0.05. A larger domain in x_{Bj}, Q^2 and t could be explored with the muon beam available at CERN.

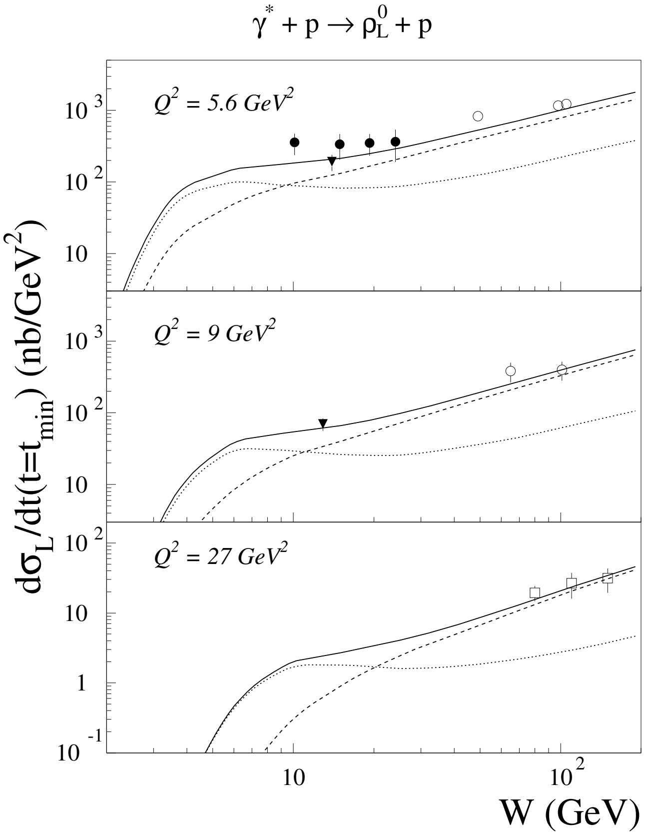

Fig. 2. Longitudinal forward differential cross section for ρ^0_L production (Fig. from [8]). Predictions reproduce quark contributions (dotted lines), gluon contributions (dashed lines) and the sum of both (full lines). The data are from NMC (triangles) [9], E665 (solid circles) [10], ZEUS 93 (open circles) [11] and ZEUS 95 (open squares) [12].

Deeply virtual Compton scattering is accessed by photon lepto-production: $lp \to l'p'\gamma$. In this reaction, the final photon can be emitted either by the leptons (Bethe-Heitler process) or by the proton (genuine DVCS process). If the lepton energy is large enough (see Fig. 3 with E_μ = 190 GeV, Q^2= 4 GeV^2, x_{Bj}=0.1), the DVCS contribution dominates over the BH contribution so that the cross section is essentially the square of the DVCS amplitude which, at leading order, has the form:

$$\begin{aligned}\mathcal{A}(\gamma^*_T) &\sim \int_{-1}^{+1} \frac{H(x,\xi,t)}{x-\xi+i\epsilon} dx ... \\ &\sim \mathcal{P}\int_{-1}^{+1} \frac{H(x,\xi,t)}{x-\xi} dx ... - i\pi H(\xi,\xi,t) ....\end{aligned}$$

(where $\xi \sim x_{Bj}/2$ and t are fixed by the experiment). At smaller lepton energy (see Fig. 3 with E_μ = 100 GeV and same values of Q^2 and x_{Bj} as above), the interference between BH and DVCS becomes large and offers a unique opportunity to study Compton scattering amplitude including its phase. A

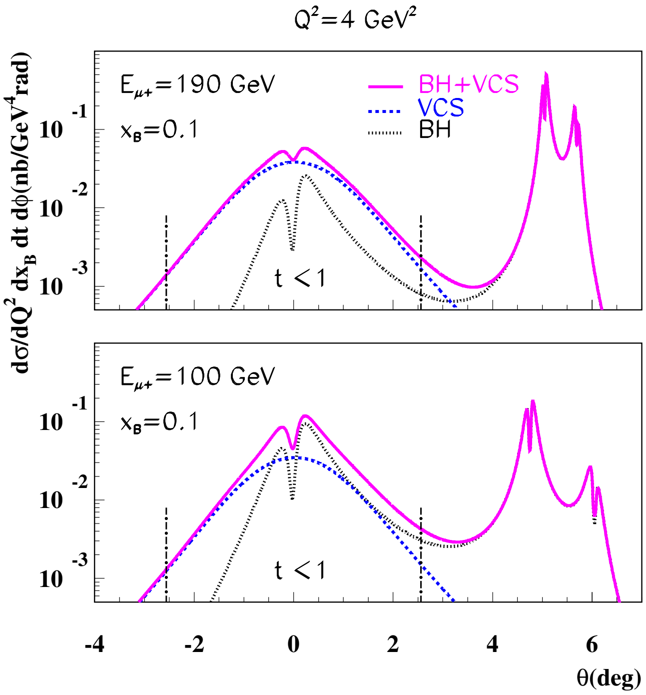

Fig. 3. Cross sections for the photon leptoproduction $\mu p \to \mu p\gamma$ as a function of the outgoing real photon angle (relative to the virtual photon direction). Comparison between BH (dotted lines), DVCS (dashed lines) and the total cross sections (full lines) for 2 energies of the muon beam available at CERN: 190 and 100 GeV. The interesting domain is limited by a transfer $|t|$ smaller than 1 GeV^2 i.e. θ investigating a small region around 0 degree.

careful analysis of the dependence of the cross section on the azimuthal angle ϕ between the leptonic and hadronic planes and on Q^2 allows one to disentangle higher-twist effects and to select the real or imaginary parts of the DVCS amplitude [13, 14]. Considering an unpolarized target, the dependence of the cross section on the angle φ, and on the charge e_ℓ and longitudinal polarization P_ℓ of the beam, can be written as follow:

$$\frac{d\sigma(\ell p \to \ell p \gamma)}{d\varphi}$$

$$= A_{BH}(cos(\varphi), cos(2\varphi), cos(3\varphi), cos(4\varphi))$$

$$+A_{INT}(cos(\varphi), cos(2\varphi))$$

$$[\ e_\ell\ [c_1 cos(\varphi) \Re e\mathcal{A}(\gamma_T^*) + c_2 cos(2\varphi) \Re e\mathcal{A}(\gamma_L^*) + ...]$$

$$+\ e_\ell P_\ell\ [s_1 sin(\varphi) \Im m\mathcal{A}(\gamma_T^*) + s_2 sin(2\varphi) \Im m\mathcal{A}(\gamma_L^*)]]$$

$$+A_{VCS}(cos(\varphi), cos(2\varphi), P_\ell\ sin(\varphi))$$

where A_{BH}, A_{INT}, c_i, s_i are known expressions and $\mathcal{A}$ represents $\gamma^* p \to \gamma p$ amplitudes for different γ^* polarization. The scaling predictions give leading twist-2 and twist-3 contributions for $\mathcal{A}(\gamma_T^*)$ and $\mathcal{A}(\gamma_L^*)$ respectively. The dotted points in brackets stand for a φ-independent term and a term with $cos(3\varphi)$ which contains twist-4 and twist-2 contributions (the latter is related to the gluon double helicity-flip distributions). Both are predicted to be small in the kinematics under study but can readily be includied in a full analysis. If a longitudinally polarized lepton beam and an unpolarized target are used, the angular analysis and the Q^2 dependence of the cross section difference $\sigma(e^\uparrow) - \sigma(e^\downarrow)$ allow one to select the imaginary part of the DVCS amplitude and thus the GPDs at the specific values $x = \xi$. This study is being investigated at HERMES [6] and JLab [5]. If two muon beams of opposite charge and polarization are used, the angular analysis and the Q^2 dependence of the sum of cross sections $\sigma(\mu^{+\downarrow}) + \sigma(\mu^{-\uparrow})$ allow also one to select the imaginary part of the DVCS amplitude. Moreover the same method applied to the difference of cross sections $\sigma(\mu^{+\downarrow}) - \sigma(\mu^{-\uparrow})$ allows one to select the real part of the DVCS amplitude which, for a given ξ, is sensitive to the complete dependence on x of the GPDs. The deconvolution (over x) of this formula to extract the GPDs is not yet clearly solved, but comparison to model predictions can easily be made. It is clear that the muon beam of high energy at CERN can offer many possibilities in order to investigate the many-faceted problem of the GPDs knowledge.

Figure 4 shows the azimuthal distribution of the charge asymmetry which could be measured at COMPASS and the strong sensitivity to two different models [15]. The first one is based on a simple parametrization of the GPDs:

$$H^f(x, \xi, t) = H^f(x, \xi, 0) F_1^f(t)/2$$

where $F_1^f(t)$ represents the elastic Dirac form factor for the quark flavor f in the nucleon. The second one [16–19] relies on the fact that the GPDs measure the contribution of quarks with longitudinal momentum fraction x to the corresponding form factor as is suggested by the sum rule:

$$\int_{-1}^{+1} H^f(x, \xi, t) dx = F_1^f(t).$$

As one can associate the Fourier transform of form factors with charge distributions in position space, one can expect that the GPDs contain information about the distribution of partons in transverse position space. In fact it has been demonstrated that, when t is purely transverse which amounts to $\xi = 0$, then $H(x, 0, t)$ is the Fourier transform of the probability density to find a quark with momentum fraction x at a given distance from the center of momentum in the transverse plane. Qualitatively one expects that quarks with a large x come essentially from the small valence "core" of the nucleon, while the small x region should receive contributions from the much wider meson "cloud". Therefore one expects a gradual increase of the t-dependence of $H(x, 0, t)$ as one goes from larger to smaller values of x. This suggests the parametrization: $H(x, 0, t) = q(x) e^{t<b_\perp^2>} = q(x)/x^{\alpha t}$ where $< b_\perp^2 >= \alpha \cdot ln1/x$ represents the increase of the nucleon transverse size with energy. The domain of small x_{Bj} reacheable at COMPASS is related to the observation of sea quarks or meson "cloud" or also gluons and it provides a large sensitivity to this three-dimensional picture of partons inside a hadron.

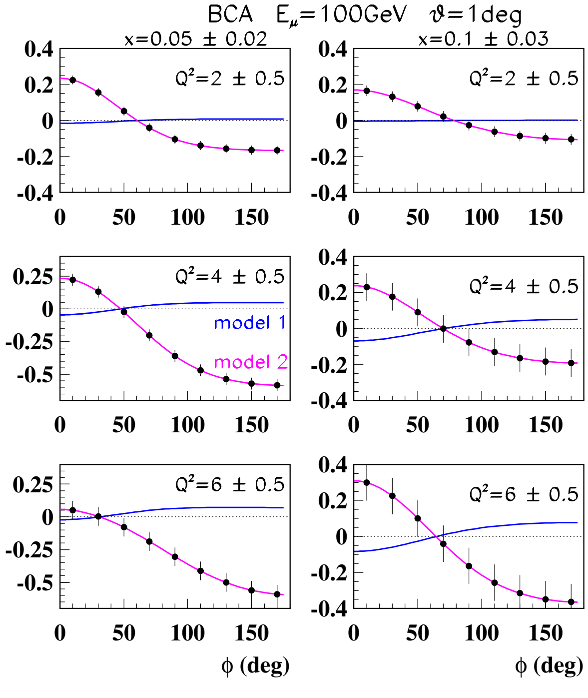

Fig. 4. Projected error bars for a measurement of the azimuthal angular distribution of the beam charge asymmetry measurable at COMPASS at E_μ= 100 GeV and $|t| \leq 0.6$ GeV^2 for 2 domains of x_{Bj} ($x_{Bj} = 0.05 \pm 0.02$ and $x_{Bj} = 0.10 \pm 0.03$) and 3 domains of Q^2 ($Q^2 = 2 \pm 0.5$ GeV^2, $Q^2 = 4 \pm 0.5$ GeV^2 and $Q^2 = 6 \pm 0.5$ GeV^2) obtained in 6 months of data taking with a global efficiency of 25% and with $2 \cdot 10^8$ μ per SPS spill ($P_{\mu^+} = -0.8$ and $P_{\mu^-} = +0.8$) and a 2.5m long liquid hydrogen target.

2 General requirements for COMPASS

The highest luminosity reachable at COMPASS is required to investigate these exclusive measurements. The experiment will use 100-190 GeV/c muons from the M2 beam line. Limits on radio-protection in the experimental hall imply that the maximum flux of muon to be expected is of $2 \cdot 10^8$ muons per SPS spill (5.2s spill duration, repetition each 16.8s). Under these circumstances, we can reach a luminosity of $\mathcal{L} = 5 \cdot 10^{32}$ $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ with the present polarized ^{6}LiD or NH_3 target of 1.2 meter long, and only $\mathcal{L} = 1.3 \cdot 10^{32}$ $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ with a new liquid hydrogen target of 2.5 meter long.

In order to get useful cross sections with positive and negative muon beams, it is necessary to perform a precise absolute luminosity measurement. This has already been achieved by the NMC Collaboration within a 1% accuracy [20]. The integrated muon flux was measured continuously by two methods: either by sampling the beam with a random trigger (provided by the α emitter Am^{241}) or by sampling the counts recorded in 2 scintillators hodoscope planes used to determine incident beam tracks. The beam tracks were recorded off-line, in the same way as the scattered muon tracks to determine exactly the integrated usable muon flux.

Moreover μ^+ and μ^- beams of 100 GeV energy, with the same and as large as possible intensity as well as exactly opposite polarization (to a few %) are required. The muons are provided by pion and kaon decay and are naturally polarized. The pions and kaons come from the collision of the SPS 400 GeV proton beam on a Be primary target. A solution is under study [21]. It consists in:
1) selecting 110 GeV pion beams from the collision and 100 GeV muon beams after the decay section in order to maximize the muon flux;
2) keeping constant the collimator settings which define the pion and muon momentum spreads (both the collimator settings in the hadron decay section and the scrapper settings in the muon cleaning section) in order to fix the μ^+ and μ^- polarizations at exactly the opposite value ($P_{\mu^+} = -0.8$ and $P_{\mu^-} = +0.8$);
3) fixing N_{μ^-} to $2 \cdot 10^8$ μ per SPS spill with the longest 500mm Be primary target; 4) using a shorter target to find N_{μ^+} close to $2 \cdot 10^8$ μ per SPS spill.

This paragraph presents the experimental procedure to select the exclusive HEMP or DVCS channel and the difference equipments that are required. They are mostly part of the existing high resolution COMPASS spectrometer: muon detection which insures a good resolution in x_{Bj} and Q^2, meson detection and identification in RICH or photon detection in calorimeters of good energy and position resolutions to allow two photons separation. The COMPASS spectrometer intercepts only forward outgoing particles (until 10 degrees) and the photon or meson detection limits the experiment to small x_{Bj} values ($x_{Bj} \leq 0.15$). At these high energies the complete final state, including the low energy recoiling proton, needs to be detected because missing mass techniques are not efficient due to the experimental resolutions (the resolution in missing mass which is required is $(m_p + m_\pi)^2 - m_p^2 = 0.25$ GeV^2 and the experimental resolution which can be achieved is larger than 1 GeV^2). Consequently the high resolution COMPASS spectrometer would need to be complemented by a recoil detector to measure precisely the proton momentum and exclude other reactions under high luminosity conditions. With the present COMPASS setup we can try to by-pass the necessity of a recoil detector to investigate the cleanest channel: $\mu p \to \mu p \rho^0$ where ρ^0s are identified through their decay in two charged pions accurately measured in the forward COMPASS spectrometer.

3 An ideal solution with a completed setup

It is clear that only a recoil detector which allows the low energy recoiling proton detection will help to select exclusive channels as HEMP or DVCS. The latter reaction is surely the most delicate because one has to select a final state with one muon, one photon and one low energy proton among many competing reactions listed below:
1) Hard Exclusive π^0 Production $\mu p \to \mu p \pi^0$ where π^0 decays in two photons, for which the photon with higher energy imitates a DVCS photon, and the photon with smaller energy is emitted at large angle outside of the acceptance or its energy is below the photon detection threshold.
2) Diffractive dissociation of the proton $\mu p \to \mu \gamma N^*$ with the subsequent decay of the excited state N^* in $N + k\pi$. (The low energy pions are emitted rather isotropically).
3) Inclusive Deep Inelastic Scattering with, in addition to the reconstructed photon, other particles produced outside the acceptance or for which tracks are not reconstructed due to inefficiency.
Moreover one has to take into account a background which includes beam halo tracks with hadronic contamination, beam pile-up, particles from the secondary interactions and external Bremsstrahlung.

A simulation has been realized in order to define the proper geometry of the detector complementing the present COMPASS setup and to analyze the operational conditions. The goal was to maximize the ratio of DVCS events over DIS events for a sample of events with one muon and one photon in the COMPASS spectrometer acceptance plus only one proton of momentum smaller than 750 MeV/c and angle larger than 40 degrees (it is the typical kinematics of a DVCS event at small t). The simulation relies on the event generator program PYTHIA 6.1 [22] which includes most of the known processes [23] such as Deeply Inelastic Scattering and Deeply Meson Production. The experimental parameters such as maximum angle and energy threshold for photon detection and maximum angle for charged particle detection could then be tuned. With photon detection extended up to 24 degrees and above an energy threshold of 50 MeV and with charged particle detection up to 40 degrees, one observes that the number of DVCS events as estimated with models is more than an order of magnitude larger than the number of DIS events over the whole useful Q^2 range (see Fig. 5).

The COMPASS setup will be instrumented with two electromagnetic calorimeters ECAL1 and ECAL2 [24,25]. They are mainly constituted of lead-glass blocks called GAMS. They are cells of $38.4 \times 38.4 \times 450$ mm^3. Typical characteristics of such calorimeter are:
- energy resolution: $\sigma P_\gamma / P_\gamma = 0.055/\sqrt{P_\gamma} + 0.015$
- position resolution: $\sigma_x = 6.0/\sqrt{P_\gamma} + 0.5$ in mm

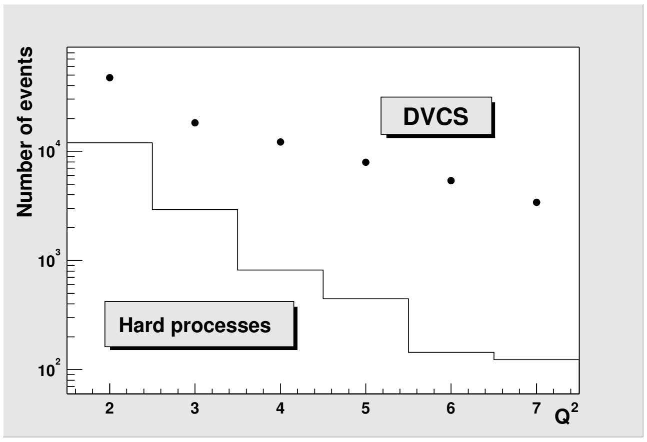

Fig. 5. Number of events for DVCS (dots) and DIS (histogram) processes as a function of Q^2 for selection of events with only one muon, one photon and one recoiling proton and condition for charged particle detection up to 40 degrees and for photon detection up to an angle of 24 degrees and above a threshold of 50 MeV.

- high rate capability: 90% of signal within 50ns gate with no dead time
- effective light yield: about 1 photoelectron per MeV; hence low energy photons of down 20 MeV can be reconstructed.

The separation of the overlapping electromagnetic showers in the cellular GAMS calorimeter is carefully studied in the Ref. [26]. The result of the study shows that at 10 GeV one can reach a 100% level of the separation efficiency for a minimum distance between 2 photon tracks at the entrance of the calorimeter of D = 4 cm. The last value is slightly shifted to D = 5 cm at 40 GeV.
This excellent performance of the calorimeters will provide a key role in the perfect separation between DVCS events and Hard π^0 events.

One possible solution to complement the present COMPASS setup is presented in Fig. 6. It consists of one recoil detector described below, an extended calorimetry from 10 to 24 degrees, and a veto for charged forward particles until 40 degrees. This calorimeter has to work in a crowdy environment and in a magnetic fringe field of SM1 and therefore it has to be studied further.

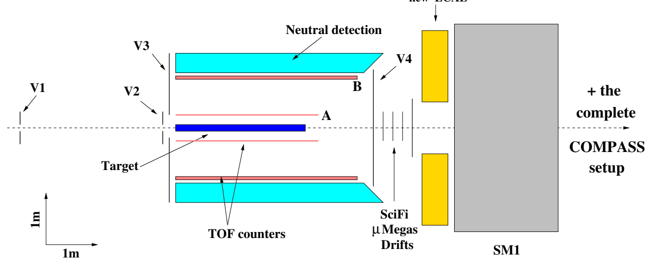

Fig. 6. Proposition for a detector complementing the COMPASS setup. A recoil detector, an extended calorimetry from 10 to 24 degrees, and a veto (V4) for charged forward particles until 40 degrees have been added.

At the present time our studies have focused on the possibility to design and successfully operate a dedicated recoil detector. One goal is to identify and measure the protons momenta between a minimum value and 750 MeV/c. A solution consists in a large time of flight setup between a thin segmented cylindrical layer of scintillator counters surrounding the 2.5 meter long target, and a thick layer at about 1m distance from the first layer. The thickness of the first layer has to be as small as possible in order to detect protons of minimum momentum. With an hydrogen target of 3cm diameter, target wall thickness of about 3mm of equivalent scintillator and a first layer of 4mm, a minimum momentum of 270 MeV/c is reached. All the counters are read at both sides by photomultiplier counters to determine time and position with very accurate resolutions better than 200ps and 1.5cm respectively. The consequent resolution in momentum varies from 2 to 5%. The resolution in t is twice this value, thus it is very desirable to further study all the parameters which can be improved. Moreover the exclusion of extra particles have to be studied with kinematical fits depending on the experimental resolution and/or with low energy π^0 detection. This detector has to work in a high rate environment. It has to be as large and hermetic as possible within a reasonable cost. The actual realisation of such performances is under active investigation. An efficiency study of such a recoil detector is being performed.

We have tested the concept of this detector using the already existing muon beam and a simplified setup (one sector of scintillators with reduced length). The muon beam was scattered off a 10 cm long polyethylene target, mostly equivalent in radiation length to the foreseen long liquid hydrogen target. We used three scintillators read-out at both sides, a 4mm thick close to the target (A), a 5 cm thick 80 cm away from the target (B) and an extra scintillator (C) to know if particles go through B or are stopped in B. The rates observed in the scintillator close to the target, using the nominal intensity of $2 \cdot 10^8$ muons per spill, is of the order of 1 MHz (mainly due to Möller electrons). It demonstrates that the background environment is acceptable for the time of flight system.

The result of the time of flight operation (see Fig. 7) shows a clear proton signal. With the knowledge of the β velocity and the energy lost in the thick scintillator (B) for stopped particles one can reconstruct their masses. It is done in Fig. 8 where one can see pions, protons and deuterons for raw data, corrected data and the target out contribution which is about two order of magnitude smaller. The position resolution obtained on A and B and the time of flight resolution are better than 1.8 cm and 300 ps respectively. The performance of this ToF system is limited by the number of photoelectrons that are collected and dispersion due to counter lenght. Extension to long (about 4 meter) and thin scintillators have to be studied carefully and technology has to be improved to achieve still better resolution. The construction of a fully functional prototype segment of the appropriate length is foreseen [27].

4 Conclusion

This study points out the advantages of the COMPASS spectrometer and the high energy of the muon beam available at CERN which would give access to a large Q^2 and x_{Bj} range

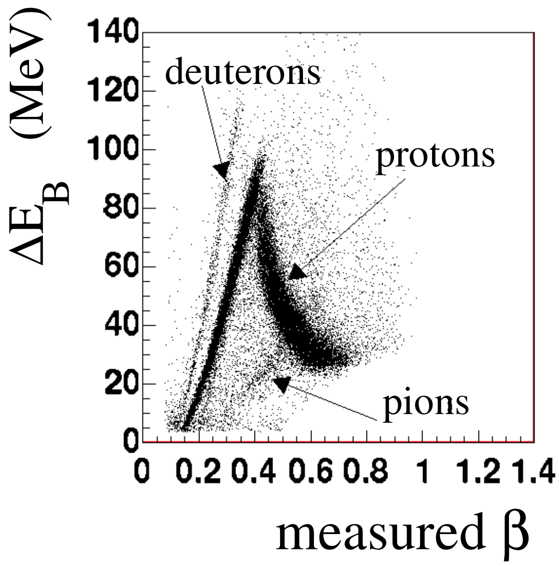

Fig. 7. Energy lost in the thick scintillator (B) as a function of the measured β.

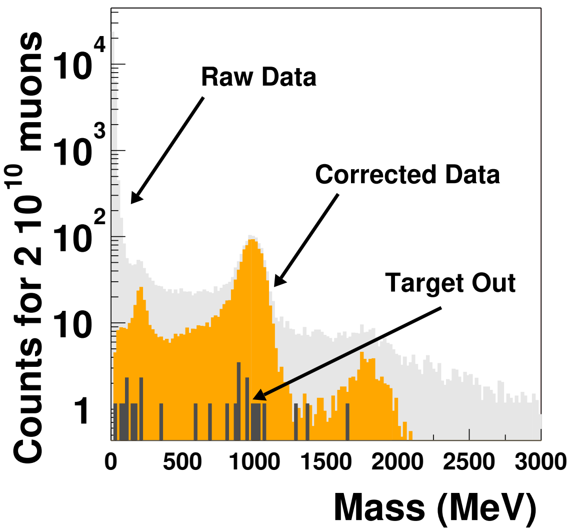

Fig. 8. Mass distribution of particles stopped in B. The three peak are pions, protons and deuterons respectively.

and encourages us for the following roadmap. Hard Exclusive Meson Production have to be undertaken as soon as possible with the present setup. The ρ^0 channel which decays in $\pi^+\pi^-$ is the easiest channel to isolate, the π^0 channel is more difficult but very important to test the calorimetry performances. A complete experiment with both Hard Exclusive Meson Production with a large set of mesons and Deeply Virtual Compton Scattering has to be envisaged in a next step with a completed COMPASS setup. For this purpose one needs a "long" hydrogen target, a recoil detector and an extension of the calorimetry at larger angles.

COMPASS is the unique place which provides μ^+ and μ^- of 100 GeV in order to study carefully two scales of observation $x_{Bj} = 0.05 \pm 0.02$ and $x_{Bj} = 0.10 \pm 0.03$ on a large domain of Q^2 from 2 to 7 GeV^2 and to measure the azimuthal distribution of the Beam Charge Asymmetry which seems very promising to test the geometrical interpretation of GPDs.

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