PEP-N Detector Layout

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The PEP-N experiment is being designed to carry out an extensive physics program which includes, among others, the measurement of R, the determination of baryon and meson form factors, and the study of exclusive multihadronic final states. In this paper we discuss the requirements on the PEP-N detector and we present the proposed layout of the experimental apparatus.

1. INTRODUCTION

We describe a possible experimental apparatus for a proposed new experiment to be carried out at an asymmetrical collider, consisting of the PEP-II Low Energy Ring (LER) and a new electron storage ring (Very Low Energy Ring, VLER) of energy $100\ MeV < E_e < 800\ MeV$. The accessible center of mass (CM) energy will then be $1.2\ GeV < \sqrt{s} < 3.15\ GeV$.

While there are many important physics measurements that are feasible at this collider, a lot of emphasis will be on R, the ratio of the hadron and muon pair cross sections, and on the determination of nucleon form factors.

This paper is organized as follows: the main physics motivations will be outlined in section 2. The measurement method of R and the experimental requirements will be the subject of section 3, while the detector requirements will be discussed in section 4. Section 5 will be devoted to rates and running time. The detector layout will then be presented in section 6. The individual detector components will be briefly described in section 7 (a full description can be found in the dedicated papers in these proceedings). Finally in section 8 we will present our conclusions.

2. PHYSICS MOTIVATIONS

There is a rich variety of important physics measurements that are accessible to an electron-positron collider in the CM energy range $1.2\ GeV < \sqrt{s} < 3.15\ GeV$. Many of these are summarized below.

2.1. The Measurement of R

The hadronic vacuum polarization diagram contributes significantly to the muon anomalous magnetic moment $a_\mu = (g-2)_\mu$ and to the evolution of the QED coupling constant α_{EM}. The value of $\alpha_{EM}(M_Z^2)$, vital for the determination of the Higgs mass, is the most poorly known of the three parameters (G_F, M_Z, $\alpha_{EM}(M_Z^2)$) that define the standard electroweak model. The calculation of a_μ has recently received great attention due to the preliminary results of BNL experiment E821, which reports a 2.6 σ discrepancy between measurement and standard model calculations. The hadronic terms contributing to the evolution of $\alpha_{EM}(M_Z^2)$ and to a_μ can be determined directly from the ratio

$$R = \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

by means of dispersion integrals. In both cases the biggest contribution comes from the low energy part of the integral.

The theoretical evaluations of a_μ^{had} fall into several classes: numerical integration of e^+e^- R data only, use of e^+e^- data plus perturbative QCD (PQCD), the use of e^+e^- data plus τ decay data. Since the use of PQCD and of τ decay data has been the subject of some controversy we will restrict our discussion to determinations of a_μ^{had} which use direct $e^+e^- \to hadrons$ data only. The situation is summarized in Table I which shows the contributions of the various energy regions to a_μ^{had} (in ppm). The four columns show the energy region, the value of a_μ^{had} for that region in ppm, the percentage error on the measurement of R and the corresponding error on a_μ. The numbers in parentheses show prospective improvements in R data coming from VEPP-2M (low energy region, data already available, their publication is in progress) and from BEPC (high energy region). It can be seen that in this scenario the biggest contribution on the error on a_μ comes from the region between 1.5 and 2.5 GeV: a measurement of R with 2 % precision in this region would bring the contribution to the error on a_μ from 0.4 ppm to 0.1 ppm, making it comparable to that in the other regions (in fact even smaller !).

Similar considerations for $\alpha_{EM}(M_Z^2)$ (for which the 1.5–2.5 GeV region is even more important) lead to the conclusion that it is extremely important to carry out a 2% (or better) measurement of R in the energy region between 1.2 GeV and 3.1 GeV.

2.2. Baryon Form Factors

Better nucleon electromagnetic form factor data will hopefully resolve many puzzles posed by the (poor) existing data

Table I The contributions to a_μ^{had} from the various energy regions

Energy range	a_μ^{had} (ppm)	δR (%)	δa_μ (ppm)
$<$ 1.4 GeV	51.6	2.0(0.6)	1.0(0.29)
1.5-2.5 GeV	3.8	10-15	0.4
$>$ 2.5 GeV	4.8	15(5-7)	0.4(0.2)

[1], in particular by the neutron timelike form factor measurement, which is several times larger than expected. Precise data will confront QCD in the interesting region between the nonperturbative and perturbative regimes. The new measurements will have much smaller statistical errors than previous experiments and will for the first time allow clear separation of the electric and magnetic form factors of the nucleon [2].

Of the hyperon form factors, only that of the Λ is (badly) measured and measurements of the Λ, charged and neutral Σ and Λ–Σ form factors will provide motivation for theoretical advances in baryon structure.

The experiment will also have the ability to measure timelike nucleon-nucleon resonance transition form factors.

2.3. Meson Form Factors

Pion and charged and neutral kaon timelike electromagnetic form factors are poorly measured above $q^2 \approx 2\ GeV^2$; vector meson form factors are essentially unmeasured. Both pseudoscalar and vector meson form factors represent potentially tractable applications of PQCD and high precision measurements are needed to complement the active ongoing theoretical efforts in this field.

2.4. Vector Meson Spectroscopy

Electron–positron annihilations are ideal for detecting 1^{--} states, of which eight have been reported in this region, but with poor determinations of branching ratios, masses and widths.

2.5. Multihadron Final States

Exclusive multihadron final states will also be measured, to search for exotic and non-exotic resonances in production, such as those recently reported in antiproton–proton annihilations at LEAR and in diffractive photoproduction at Fermilab [3].

3. EXPERIMENTAL REQUIREMENTS

The most challenging item in the PEP-N physics program is the high precision measurement of R. For this measurement the detector should have as high an acceptance as possible. Two methods can be used to measure R:

- **Inclusive approach:** with this method hadronic events are defined inclusively by requiring a minimum number of particles in the detector. In order to measure the cross section $\sigma(e^+e^- \to \text{hadrons})$ from this inclusive measurement one needs to correct for the overall acceptance, which is a superposition of acceptances for the various channels contributing to R and which must be estimated by means of Monte Carlo simulation. This leads to potentially large systematic errors related to the theoretical modelling used in the Monte Carlo, which make this method unsuitable for a high-precision (1–2%) measurement of R.

- **Exclusive approach**: this method consists in the measurement of the cross section of each individual channel contributing to R. It requires the ability to reconstruct events completely with high efficiency, along with the capability to determine acceptances for each channel with very high accuracy. This can be achieved by designing a detector able to measure the absolute position of charged and neutral particles. With this method an accuracy of 1–2% in the measurement of R can be reached, as shown by the recent VEPP-2M measurements.

Since our goal is the measurement of R with a precision of the order of 2% (or better), the experiment must have the capability to use the exclusive method.

The study of nucleon form factors requires the additional ability to detect neutrons and antineutrons. It should be noted that the $e^+e^- \to n\overline{n}$ cross section is a sizeable fraction of the total hadronic cross section (e.g. 2.5% at $\sqrt{s} = 2\ GeV$), therefore some level of $n\overline{n}$ detection capability is needed also for the measurement of R.

4. DETECTOR REQUIREMENTS

The PEP-N detector must be able to reconstruct hadronic events completely with high efficiency (both for the R measurement and for the study of multihadronic final states and vector meson spectroscopy) and to detect $N\overline{N}$ final states. The detector design for PEP-N must take the following requirements into account:

- **Low mass tracking.** In the energy range of PEP-N multiple scattering contributes significantly to the momentum resolution ($\approx$ 2%);

- **Momentum measurement with good accuracy.** A high-precision measurement of R requires the ability to recontruct efficiently every individual final state. This can be done by means of topological selections and kinematic fitting. The possibility to identify each channel contributing to R will thus depend crucially on a high-precision measurement of the momentum.

- **Electromagnetic (EM) calorimetry.** The EM calorimeter will have to measure direction and energy of photons from neutral pion decays with high precision and accuracy down to very low energy (below 100 MeV).

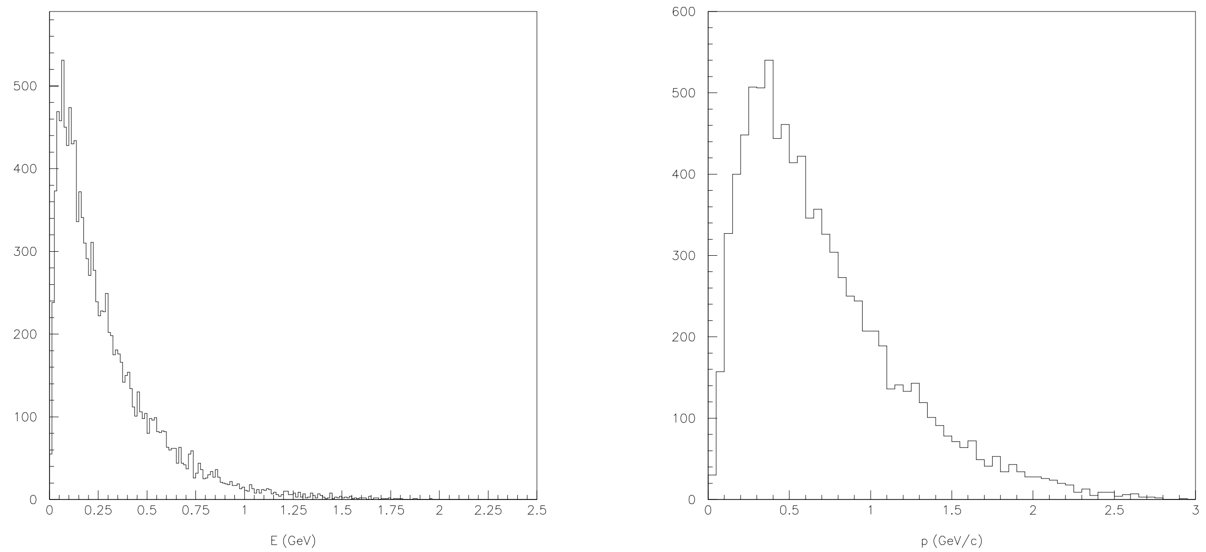

Figure 1: Energy distribution for photons (left) and momentum distribution for charged hadrons (right) from Monte Carlo simulation.

Figure 1 (a) shows the photon energy distribution generated by means of a Monte Carlo simulation [4]. EM calorimetry is also needed to measure Bhabha events, which will be used for the luminosity measurement.

- **Particle ID** is necessary for π/K separation; this feature is crucial to reconstruct efficiently final states containing pions and kaons.
- **Luminosity measurement** with an accuracy of the order of 1% or better.
- $N\overline{N}$ **capability** needed both for the neutron form factor and the R measurements.

A key feature of the proposed PEP-N facility is the fact that it is an asymmetric machine: the CM system is boosted with respect to the lab frame, with $0.6 < \beta_{cm} < 0.94$. As a consequence even slow particles (in the CM) are boosted to momenta ranging from a few hundred MeV to 1–2 GeV, as illustrated in Figure 1(b), which shows the charged particle momentum distribution generated by Monte Carlo. This makes their detection easier and it enhances the capabilities for particle ID. Moreover the more limited angular coverage needed makes the apparatus smaller and thus less expensive. The asymmetric option is also better from the accelerator point of view, because it makes beam separation easier.

Another important feature of the PEP-N design is the magnet. The magnetic field field required to perform beam separation with minimal interference with PEP-II operations is a weak dipole field ($B \approx 0.3\ T$). This field will also be used by the experiment for the measurement of charged particle momenta; therefore the tracking system will be housed inside the magnet gap which, as a consequence, has to be made big enough to give a suitable acceptance.

5. RATES AND RUNNING TIME

The rates for the processes we wish to study vary over a significant range. The muon pair cross section at $\sqrt{s} = 2\,GeV$ is 21.7 nb so that taking $R \approx 2$ the hadronic cross section is $\approx 43\,nb$. The cross sections for the processes $e^+e^- \rightarrow p\overline{p}$ and $e^+e^- \rightarrow n\overline{n}$ are about 1 nb in the region of interest, decreasing with CM energy.

Assuming an average instantaneous luminosity of $5 \times 10^{30} cm^{-2}s^{-1}$ and a detection efficiency of 50 % the expected hadronic event rate for the measurement of R is 10000 events per day. A 1–2 day data taking period at each CM energy provides more than 10000 events per point giving cross section measurements with statistical accuracies better than 1%. We anticipate taking data at intervals of 10 MeV, leading to several hundred days of data taking needed to cover the energy region between 1.2 GeV and 3.15 GeV.

Under comparable conditions the expected event rate for $N\overline{N}$ final states is 200 events per day. A 10 day data taking period at each CM energy provides about 2000 events per point giving cross section measurements with statistical uncertainties below 3%.

Taking a maximum total cross section of 100 nb and maximum possible instantaneous luminosities of $10^{31} cm^{-2}s^{-1}$ the maximum event rate (excluding backgrounds) is 1 Hz. Even considering backgrounds rates should be well below the limit of capability for the detectors we discuss.

6. DETECTOR LAYOUT

The proposed PEP-N detector layout is shown in Figure 2. It consists of the dipole magnet and of central (i.e. inside the magnet) and forward detector elements.

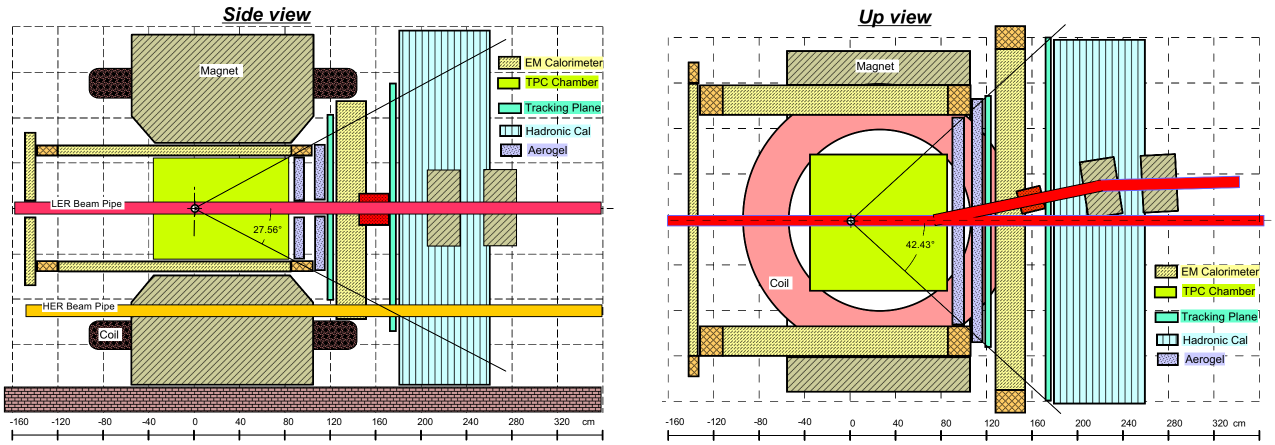

Figure 2: PEP-N detector layout: side view (left) and top view (right).

The central detector is housed inside the gap of the magnet: it consists of a time projection chamber (TPC) and of EM calorimeter modules located on the magnet poles (PCAL), along the side (BCAL) as well as in the backward direction (RCAL).

The dipole magnet and the central detector are not centered on the interaction point, but they are shifted 25 cm in the forward direction, to increase the path inside the magnetic field for the forward produced particles.

The forward detector consists of two silicon aerogel counters for particle ID, additional tracking planes (drift chambers) as well as EM and hadronic calorimeter modules.

Also shown in Figure 2 are the HER (High Energy Ring), LER and VLER beam pipes, as well as various accelerator bending magnets.

7. DETECTOR COMPONENTS

The individual detector components are discussed in great detail in the dedicated papers in these proceedings. In what follows we give only a brief description of the main features of each element.

7.1. Magnet

The dipole magnet provides the vertical B field needed for beam separation. It is also used to measure the momenta of charged particles. Its gap houses the central tracking and calorimeter systems, and therefore it must be big enough to give adequate acceptance. As a consequence, the B field has a limited degree of uniformity and moreover it extends well outside the magnet itself. The design of the magnet has thus required extensive simulation to maximize the field uniformity, which is very important for a smooth operation of the tracking detector [5].

7.2. Tracking

The tracking system must reconstruct the trajectories of charged particles to measure their momenta with good precision. The main requirements on the tracking are:

- good space resolution (200–300 μm);
- dE/dx capability (for particle ID, particularly at low momenta);
- low mass, to minimize multiple scattering;
- minimize dead spaces (frames, supports etc) which limit the acceptance and reduce the sensitivity to low energy photons.

The central tracking must operate in a nonperfectly uniform magnetic field.

A TPC with a slow, He based gas (to minimize distortions due to magnetic field non-uniformity) meets the above requirements. The use of a multi GEM detector (instead of wires) will eliminate the $E \times B$ term in the resolution, leading to better and more uniform spatial resolution [6].

The forward tracking chambers will be used to correct distortions in the TPC, they will serve as veto for neutrons and they will help with muon identification.

7.3. EM Calorimeter

The EM calorimeter will be used primarily to identify photons from neutral pion decays and $e^+e^- \to e^+e^-$ Bhabha events. The main requirements are:

- high acceptance;
- good efficiency and good energy resolution (few %) down to low energies (below 100 MeV);
- good time resolution.

A lead and scintillating fiber calorimeter based on the KLOE design meets all the above requirements [7].

7.4. Particle ID

Particle identification is achieved by means of two aerogel counters, each 10 cm thick (total thickness 0.15 radiation lengths), which can achieve 4σ $\pi - K$ separation in the momentum range between 600 MeV/c and 1.5 GeV/c [8]. The design of these counters is based on the detectors built for the KEDR experiment in Novosibirsk.

Below 600 MeV/c particle ID will be based on dE/dx in the tracking chambers as well as time-of-flight (TOF) in the forward EM calorimeter [7].

7.5. Hadron Calorimeter

The hadron calorimeter will be used mainly for $n\overline{n}$ identification, therefore it should be highly efficient both for neutrons and antineutrons. In addition it should provide TOF and position measurements for both n and $\overline{n}$.

The hadron calorimeter can be built as a scintillator calorimeter using MINOS technique [9]. In alternative it can be an extension of the electromagnetic calorimeter (based on the KLOE design), with a sampling fraction optimized for the detection of neutrons and antineutrons.

7.6. Luminosity Monitor

The online measurement of the luminosity, required for machine tuning and monitoring, can be implemented using a PEP-II type monitor, based on single Bremsstrahlung at zero degrees.

Offline, the necessary 1% accuracy in the integrated luminosity measurement can be achieved using Bhabha events [10].

8. CONCLUSIONS

The PEP-N detector is being designed to perform a high precision (2% or better) measurement of R, a new determination of baryon and meson form factors and study of various multihadronic channels. The main design criteria, needed to accomplish these measurements, are: the capability to reconstruct efficiently exclusive final states (for the measurement of R using the exclusive approach) and to detect $N\overline{N}$ events for the measurement of nucleon form factors (as well as R).

We have presented a detector layout capable of achieving these goals. More work is in progress to develop further the PEP-N detector concept.

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