Letter of Intent

A Physics Program Emphasizing Nucleon Timelike Form Factors using PEP-II at $1.4 < \sqrt{s} < 3.1$ GeV

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We propose a physics program to be carried out using the PEPII storage ring operating at low center of mass energy ($1.4 < \sqrt{s} < 3$ GeV). The main emphasis is on a new measurement of the nucleon timelike form factors. New data will help answer many puzzles posed by the present data, in particular by the neutron timelike form factors measurements, which has been found to be several times larger than expected, and confront QCD with precise data in the interesting region between the non- perturbative and perturbative regimes. The new measurements should have much smaller statistical errors than previous experiments and would for the first time allow clear separation of the electric and magnetic form factors. At the same time the total multihadronic cross section $\sigma_{tot}(e^+e^- \to hadrons)$ can be measured with good statistical and systematic precision. The uncertainties in existing data in the region ($1.4 < \sqrt{s} < 3$ GeV) lead to substantial errors in the Standard Model predictions for quantities such as the muon $g-2$. The proposed new data would reduce the Standard Model uncertainty to a level below the expected statistical error on $g-2$, greatly improving the discovery potential of this and other similar experiments. Specific hadronic final states will also be measured with good mass resolution to search for unexpected narrow resonant states, such as those been recently observed in various experiments in the proposed mass region.

Two possible options have been considered: the use of PEPII as a collider at $\sqrt{s} \sim 2$ GeV; or the use of one of the PEPII rings for a linac-storage ring collider, parasitic to the operation for BaBar. Both options should provide a substantial gain in integrated luminosity compared to existing data in this mass region after only a few months of operation.

I. THE PHYSICS CASE OF THE NUCLEON TIMELIKE FORM FACTORS

The form factors of the proton and neutron are fundamentally important in that they describe the bound state properties of three valence quarks in the configuration that dominates the known baryonic matter in the universe. The form factors embody the probability that a nucleon will remain intact after absorption of a virtual photon with four-momentum transfer Q^2, as shown in Fig. 1, where we define the form factors to be space-like for $Q^2 < 0$, and time-like for $Q^2 > 0$.

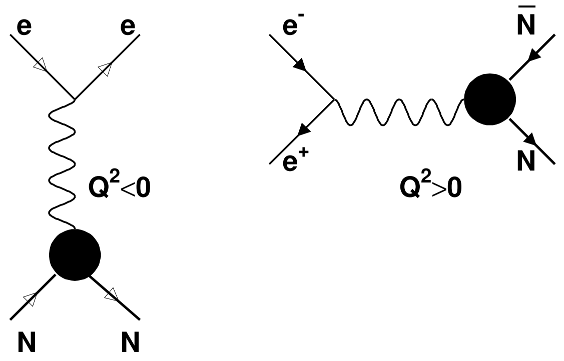

FIG. 1. Feynman diagrams containing the nucleon form factors

Confronting nucleon form factor data with QCD-based models of quark bound states is one of the most important ways of pinning down parameters of the models, which then can be used to predict other observables. At small Q^2 scales the form factors can be thought of as describing the distribution of charge and magnetization current within the nucleons, while at high Q^2 they probe the valence quark distribution functions at high relative momentum [9], with the dominant Feynman diagram being the exchange of two gluons. As QCD models develop, which can describe the full range of Q^2 from the non-perturbative regime near threshold to the perturbative regime at very large Q^2, nucleon form factor data will be crucial in testing the validity and applicability of these approaches to solving QCD.

A great deal of effort has been put into elucidating the form factors in the space-like region, with ongoing efforts at several laboratories to improve the separate determinations of both electric and magnetic form factors of both the proton and neutron over an increasingly large Q^2 range, and also to determine the strangeness form factors.

Much less is known about the time-like form factors. Even so, many questions have been raised by the existing data [10] and there is clearly a strong case [5] [6] to be made for new measurements of the neutron time-like electric and magnetic form factors. In addition, measurements that separate the electric and magnetic (or equivalently the Pauli and Dirac) form factors of the proton are called for by the surprisingly strong variation with Q^2 of the existing data near threshold, in which the form factors were not separately measured. This strong Q^2 dependence may be related to unexpected narrow structures in multihadronic cross sections which have been observed near the $N\overline{N}$ threshold. For this reason it is important to make improved measurements of multihadronic cross sections with good mass resolution in a variety of channels in addition to measuring the nucleon form factors directly.

At present, predictions on nucleon form factors mainly concern the high $|Q^2|$ behavior and apply to the spacelike and timelike region. Analyticity relates timelike and spacelike form factors, predicting a continuous transition and in particular the Q^2-dependence high $|Q^2|$ should be the same for timelike and spacelike form factors. This is also predicted by PQCD [9], which in addition specifically predicts $F_1(Q^2) \propto \alpha_S^2(Q^2)/Q^4$ and $F_2(Q^2) \propto \alpha_S^2(Q^2)/Q^6$, where $\alpha_S(Q^2)$ is the strong coupling constant, $F_1(Q^2)$ is the non-spin flip form factor and $F_2(Q^2)$ is the spin flip form factor, which decreases with an extra power of $1/Q^2$ due to helicity conservation. Both PQCD [2,3] and analyticity [4] predict a small ratio of neutron to proton form factors, namely $(G_M^n/G_M^p)^2 \sim (q_d/q_u)^2 \sim 0.25$ in both the timelike and spacelike regions. This prediction is expected to hold also in the threshold region using PQCD folded with dispersion relations [5,6], assuming the presently known vector meson spectrum. Details of the form factor definitions are given in Appendix I.

There are several unexpected experimental features in the existing data for timelike form factors that motivate the need for a new high statistics experiment with the ability for the first to to separately measure the electric and magnetic form factors (or equivalently F_1 and

F_2). These are summarized as follows:

- Ratio between neutron and proton form factors: The measurements of the neutron magnetic timelike form factors are shown in Fig.2, as obtained primarily by FENICE [10]. Two further measurements by DM2 at DCI are included [11], at $Q^2 = 5.75$ GeV^2 on the basis of two candidate events, and from the Λ timelike form factors according to U-spin invariance (that is $G_M^n \sim 2G_M^\Lambda$) [12]. Remarkably enough the neutron magnetic form factor turns out to be larger than the proton's, at variance with the expectation of a small ratio from most models. As a matter of fact any calculation based on the contribution coming from the valence quarks can hardly provide such a large neutron magnetic form factor. Large neutron to proton ratios have been predicted by pushing parameters in a few effective low-energy VDM [7] and Skyrme [8] models, but this is the exception rather than the rule.

  Part of the explanation for the large neutron to proton ratio could come from the assumption made in extracting G_M from the experimental cross section (like for instance $G_M^n \gg G_E^n$ and $G_E^p = G_M^p$, which must be true exactly at threshold, as shown in the Appendix I, but might well be false just above threshold). A new high statistics measurement is needed to separate electric and magnetic form factors and obtain an *ansatz*-free determination of both the ratios G_M^n/G_M^p and G_E^n/G_E^p as a function of Q^2.

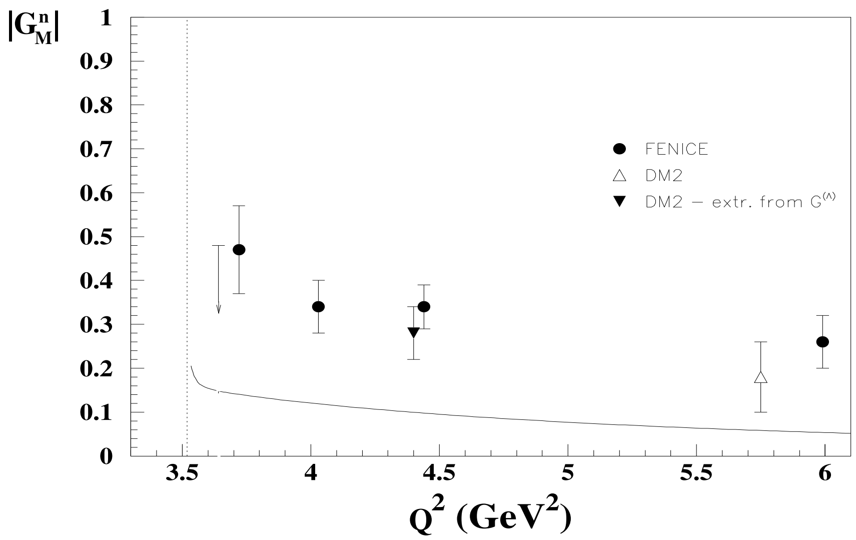

FIG. 2. Neutron magnetic form factor in the timelike region. The solid line represents a PQCD based prediction for the asymptotic behavior $|G_M^n| = 0.5\ |G_M^p|$. The dotted line indicates the $n\overline{n}$ threshold.

- The proton magnetic form factors show a strong Q^2-dependence very near threshold. The best accuracy has been achieved by the PS-170 experiment at LEAR [13], which has observed very near threshold a very sharp decrease in the form factor with increasing Q^2, as shown in Fig. 3 (a). Again, the data were extracted from cross sections assuming $G_E = G_M$ at all values of Q^2.

  In the case of the neutron, it is possible that we also observe a strong Q^2-dependence near threshold. The existing statistics-limited data from FENICE [10] are more compatible with a non isotropic angular distribution than an isotropic one, suggesting $G_M^n \gg G_E^n$ in the explored energy range. Because exactly at threshold the relationship $G_M(4M^2) = G_E(4M^2)$ (see Appendix I) must hold, the strong Q^2-dependence would mainly come from the G_E contribution to the cross section.

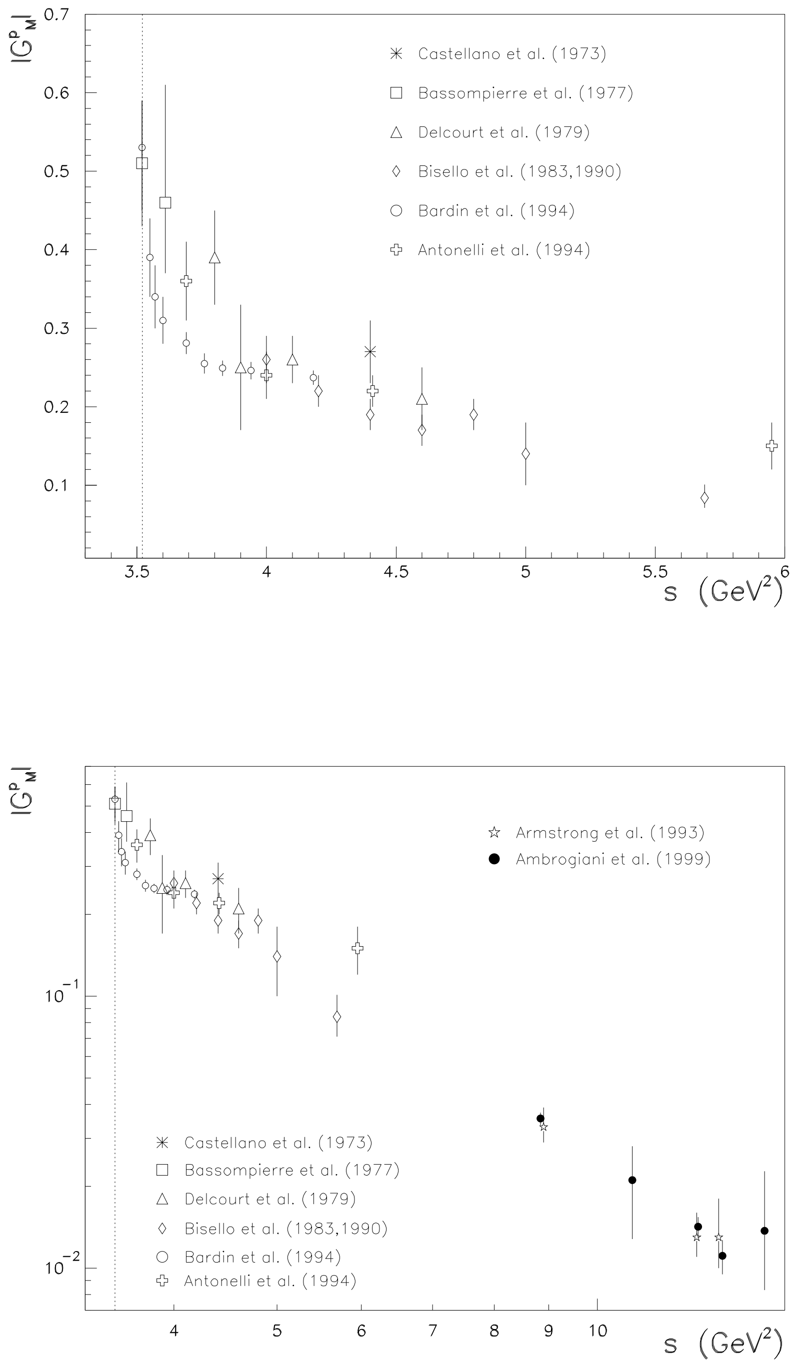

FIG. 3. Proton timelike form factor: (a) low $|Q^2|$, (b) high $|Q^2|$. The dotted line indicates the $p\overline{p}$ threshold.

On the other hand, if it turns out that the two form factors are similar and their ratio has only a weak Q^2-dependence (that is $G_E^n \sim G_M^n \sim 0.35$ at 4 GeV^2), the existing data imply a very large ratio between the timelike and spacelike electric form factors for $Q^2 = -4$ GeV^2, considering that existing data on G_E^n in the spacelike region are consistent with zero in this Q^2 region.

- In the Q^2 range explored up to now high Q^2 predictions are partially fulfilled, with the proton magnetic timelike form factor remaining substantially larger than the spacelike one measured at the same $|Q^2|$.

  The various measurements of the proton magnetic timelike form factor [13,14] are shown in Fig.3. The expected high Q^2 behavior $1/Q^4$ [15] is reached quite early, however there is a factor of two between timelike and spacelike form factors. The same factor is observed in the pion form factor; in this case a qualitative explanation has been suggested in an improved PQCD analysis in terms of integrable singularities of the propagaters [16]. Disentangling electric and magnetic form factors would allow for a better understanding of the high Q^2 behavior.

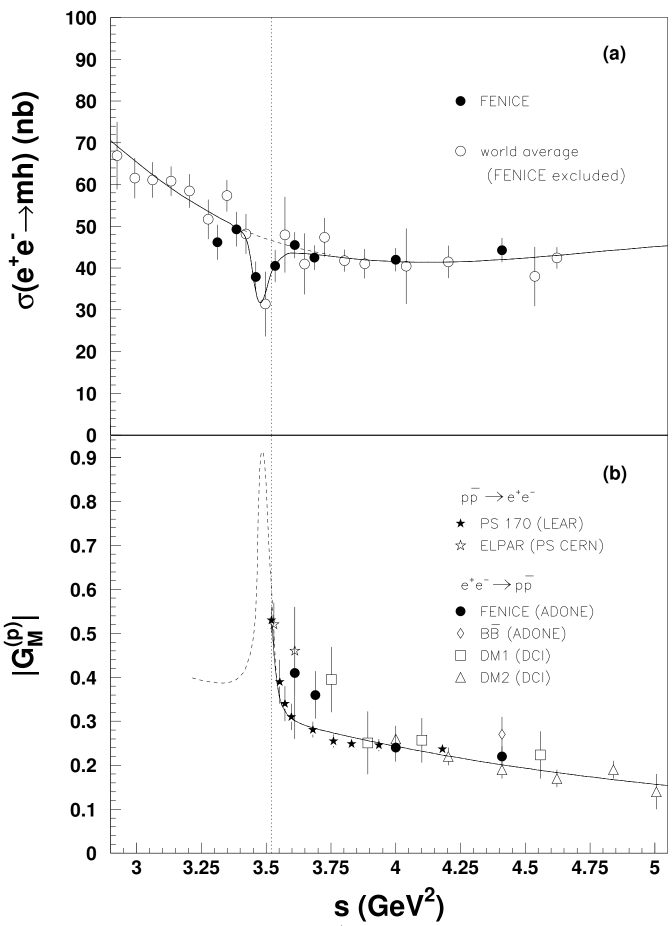

FIG. 4. (a) Total multihadronic cross section (FENICE data and the average over previous experiments) with superimposed the result of the fit to a narrow resonance close to the $N\overline{N}$ threshold; (b) comparison of the proton FF data to the expected behavior for the presence of such a resonance. The dotted line indicates the $p\overline{p}$ threshold.

- The steep Q^2-dependence to the proton form factor near threshold [10,13] suggests a relatively narrow structure at the boundary of the unphysical region, which should be seen also in multihadronic e^+e^- annihilation across the $N\overline{N}$ threshold [17]. Anomalies are indeed seen in the total cross section $\sigma_{tot}(e^+e^- \rightarrow hadrons)$ and in some multihadronic e^+e^- annihilation channels.

  The dip in the total multihadronic cross section and the steep variation of the proton form factor near threshold (see Fig. 4) may be fitted with a narrow resonance, with a mass $M \sim 1.87$ GeV and a width $\Gamma \sim 10 \div 20$ MeV. The small cross section variation and the small width suggest that the coupling to e^+e^- and to multihadronic states are small, and therefore it's influence is observed by via mixing to a broad vector meson near by, as for instance in (Fig.5). In this case the corresponding amplitude will indeed have a dip at $\sqrt{s} = M_0$, as it has been demonstrated [18] in a different context :

$$A \propto \frac{1}{s - M_V^2} \cdot (1 + a\frac{1}{s - M_0^2}a\frac{1}{s - M_V^2} + ..) \propto \frac{s - M_0^2}{(s - M_V^2)(s - M_0^2) - a^2},$$

where the complex number M_V stands for mass and width of the broad near by vector meson V, M_0 is the same for the narrow resonance V_0 and a is the V_0V coupling constant.

This narrow resonance would be consistent with the hypothesis of an $N\overline{N}$ bound state (Fig.5), predicted a long time ago [19] [20] [21] [22] [23], subsequently claimed to have been found, then disclaimed several times. However the aforementioned data in e^+e^- annihilation are fully compatible with the present data in $N\overline{N}$ annihilation.

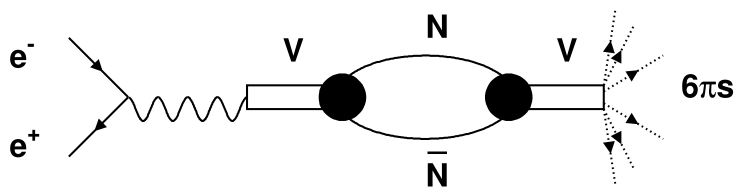

FIG. 5. Diagram describing the e^+e^- annihilation via an intermediate $N\overline{N}$ bound state.

A similar structure has been detected by DM2, as shown in Fig.6, in the $e^+e^- \to 6\pi$ channel, which is the multihadronic channel with the largest cross section at these c.m. energies. It is well established that high energy diffractive photoproduction and e^+e^- annihilation are related. Recently very high statistics and very good mass resolution have been achieved in photoproduction and still that structure, with much better statistical accuracy, has been observed by E687 at FNAL in diffractive photoproduction of $3\pi^+3\pi^-$ and also by E831 [24]. Evidence of other narrow and unexpected structures are under investigation in other channels in the same high statistics and high mass resolutions diffractive photoproduction sample.

New high statistics and good mass resolution data in the mass range $1.4 < \sqrt{s} < 3$ GeV will help to pin down the mass and widths of these new resonances, and determine their influence on the nucleon time-like form factors.

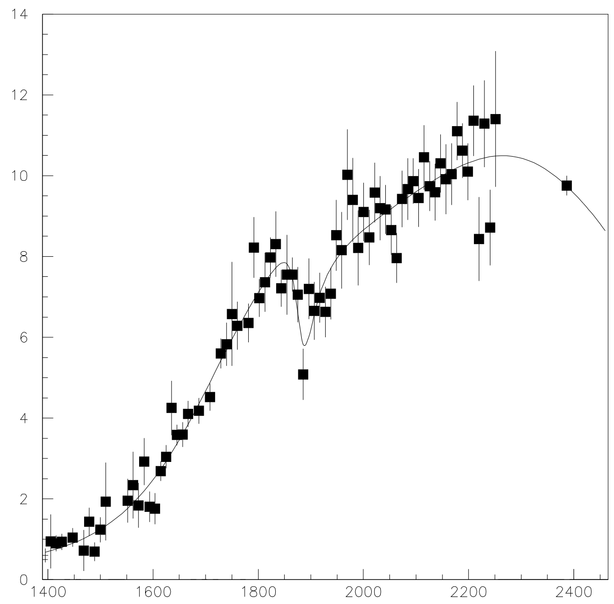

FIG. 6. Cross section for $e^+e^- \to 6\pi$ measured by the DM2 experiment.

- The nucleon form factor in the unphysical region below the $N\overline{N}$ threshold, where the structures discussed above should show up, can in principle be calculated from the space-like data by means of dispersion relations and many attempts in this direction have been made in the past. Unfortunately, in order to get a stable solution an improvement in statistical accuracy of many orders of magnitude over present spacelike data would be needed. On the contrary good data in the timelike region should allow a stable solution. A recent evaluation of the magnetic form factors in the unphysical region [25] has shown once more unexpected features, which might be related to all the properties of the timelike form factors discussed above.

All these features of the nucleon timelike form factors underline the necessity of a new measurement of neutron and proton with much higher statistics, disentangling electric and magnetic form factors, especially very close to threshold. Such a new measurement would significantly improve our knowledge of the form factors also in the unphysical region.
In the case of the proton form factor measurement very near threshold questions have been raised because of various complications in stopping $\overline{p}$ in a target [26]. An e^+e^- collider, in contrast to $p\overline{p}$, will avoid these complications, albeit at the expense of a smaller cross section.

Near and below the threshold a measurement of the various multihadronic e^+e^- channels is also of great importance to understand if there are indeed $N\overline{N}$ bound states. A statistical accuracy at least similar to what has been achieved in the case of diffractive photoproduction is needed. Of course e^+e^- annihilation allows for a much better mass resolution in a search for narrow structures.

II. OTHER, COMPLEMENTARY, MEASUREMENTS

The detector needed to measure the nucleon time-like form factors (tagged by $p\bar{p}$ and $n\bar{n}$) could be enhanced to become suitable also for other, complementary, measurements. Increasing the energy range in measuring multihadronic cross sections might several other important fundamental physics topics to be investigated:

- Measurement of the total cross section $\sigma_{tot}(e^+e^- \to hadrons)$.

  There is a serious lack of high quality data in the region $1.4 < \sqrt{s} < 3$ GeV, which results in a considerable uncertainty in the evolution of the electromagnetic coupling α to the mass scale of Standard Model measurements, for example $(g-2)$ for the muon, and A_{LR} for (e^+e^-) scattering at the Z pole [27] [28]. Even considering the recent data from Beijing, there is a lack of data in fine energy bins with statistical and systematic errors both in the few percent range, which would be needed to reduce the error on the Standard Model predictions to an acceptable level. As an example, the eventual goal of the Brookhaven $(g-2)$ experiment is a statistical error of 0.3 ppm, while the error on the Standard Model prediction due to the uncertainty in α is approximately 0.6 ppm [29]. New measurements of $\sigma_{tot}(e^+e^- \to hadrons)$ with a few percent total error and spanning 30 to 50 energy bins in the 1.4 to 3.0 GeV region would reduce this error to roughly 0.1 ppm, or about three times less than the projected statistical error on $(g-2)$. Thus, good measurements of σ_{tot} in this mass region are crucial to interpreting experiments that search for physics beyond the Standard Model at scales higher than the τ mass, such as the muon $(g-2)$ experiment and the many of the precision Z-pole measurements from SLAC and LEP.

- Measurement of the strange baryon form factors.

  The expected cross sections, at their maximum value near threshold, are smaller than the corresponding nucleon cross section. On the other hand additional information from ϕ and θ angular distributions of the decay products of the strange baryon should help, in particular in disentangling electric and magnetic form factors.

- An accurate search for small and narrow structures in the whole $1.5 \div 3$ GeV c.m. energy range, motivated by the above mentioned observations near the $N\overline{N}$ threshold.

- At higher c.m. energies a detector specialized in detecting $n\overline{n}$ should also be able to measure $\gamma\gamma \to n\overline{n}$. A recent measurement by the CLEO collaboration [30] has found $\sigma(\gamma\gamma \to \Lambda\overline{\Lambda}) \sim \sigma(\gamma\gamma \to p\overline{p})$ (larger than expected) and U-spin arguments suggest that even in $\gamma\gamma$ reactions $n\overline{n}$ production is not smaller than $p\overline{p}$. Once more electromagnetic interactions of baryons do not seem to behave as expected.

III. EXPERIMENTAL LAYOUT

A new measurement is worthwhile if there is a gain of at least an order of magnitude in the statistical accuracy and in the quality of the data. In the case of the neutron form factor measurement an integrated luminosity of about 0.5 pb^{-1} was collected, with an average instantaneous luminosity $\sim 0.5 \cdot 10^{29}$ cm^{-2} s^{-1}. Hence an average instantaneous luminosity $\sim 0.5 \cdot 10^{31}$ cm^{-2} s^{-1} or more is required. Appendix II reports a parameter study to explore the possibility to transform PEP-II into an asymmetric collider operating around 2 GeV and Appendix III reports a preliminary study to explore the possibility to use the LER of PEP-II for a linac-storage ring asymmetric collider.

Let us consider the option of lowering the PEPII energy first. It is shown in Appendix II that with reasonable assumptions on the machine parameters luminosities in excess of 1×10^{30} cm^{-2}s^{-1} can be obtained. Energy asymmetries up to $r_E = 2$ have been considered, where r_E is the ratio between the electron and the positron beam energies, for a corresponding cms velocity $\beta_{cm} = 0.33$. Boosting the velocity avoids problems in detecting neutrons with a very low kinetic energy, thus increasing the detection efficiency near threshold.

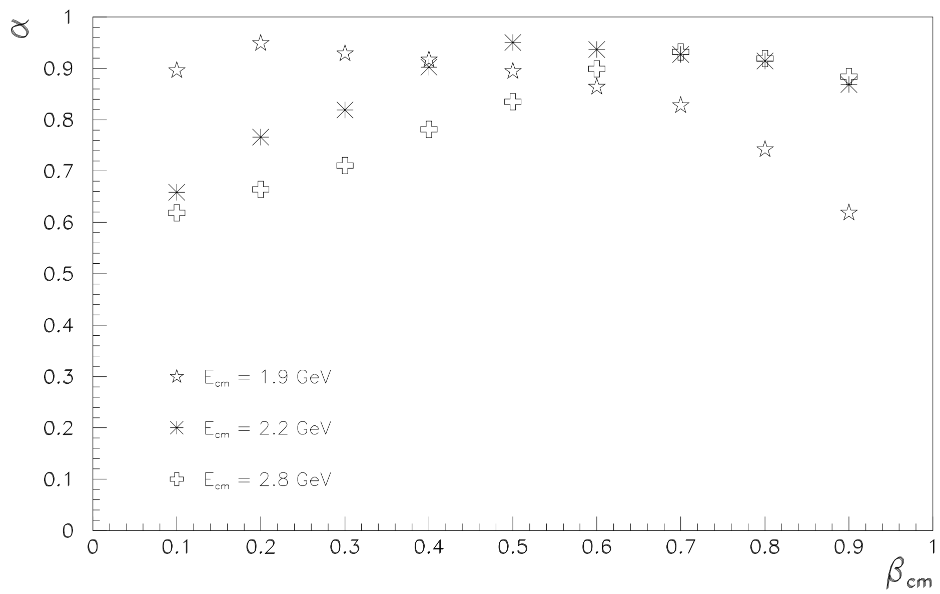

FIG. 7. Geometrical acceptance as a function of β_{cm} for $n\overline{n}$ events.

Fig. 7 shows the geometrical acceptance α for $n\overline{n}$ events as a function of β_{cm} for three values of the c.m. energy and with the angular coverage discussed below.

The many charged prong topology of $\overline{n}$ annihilation and the relatively long time of flight between production and annihilation are the signatures that allow for identification of candidate $n\overline{n}$ events. This requires a specialized $\overline{n}$ detector with tracking capabilities. Such a device would also be able to detect the highest-energy neutrons through their hadronic shower. Low energy neutron detection, if needed, requires a specialized detector, to be matched with this device.

The main goal of this experiment is the measurement of $n\overline{n}$ and $p\overline{p}$. In order to be able to also study $\Lambda\overline{\Lambda}$, $\Sigma\overline{\Sigma}$ and exclusive multihadronic final states, we need a magnetic detector with good tracking and π/K separation. Measurements of the total cross section require good angular coverage and hermeticity.

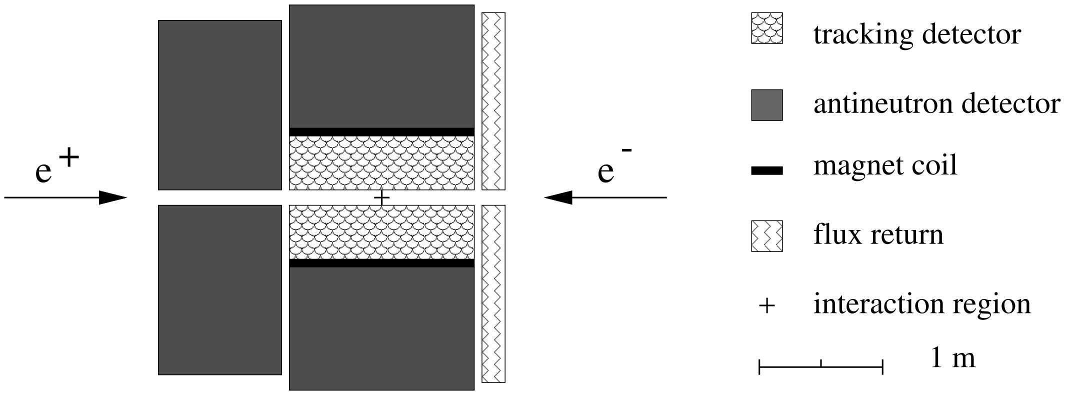

FIG. 8. Sketch of the experimental apparatus (side view).

The conceptual layout of a possible detector is schematically shown in Fig. 8. It is a magnetic spectrometer with cylindrical symmetry around the colliding beams axis, providing full azimuthal coverage and polar angle acceptance $2^\circ < \theta < 145^\circ$, where θ is measured with respect to the electron beam axis. With this arrangement the geometrical acceptance for $n\overline{n}$ and $p\overline{p}$ events is bigger than 70% at all energies and bigger than 90% at threshold for $\beta_{cm} = 0.33$. Furthermore such a detector provides a high acceptance for the multihadron final states; for instance, it is of the order of 70% for full containment of 4 π and 6 π events.

The apparatus could consist of a solenoidal magnet, a tracking chamber inside the magnet, a barrel $\overline{n}$ detector and a forward plug. The magnet should provide a field of the order of a few kG with a good homogeneity.

The tracking chamber must reconstruct the trajectories of charged particles with good resolution, better than 200 μm. A conventional gas chamber (like a TPC) could provide this performance, together with a good measurement of dE/dx for particle identification (FWHM resolution $\approx 15\%$).

The barrel $\overline{n}$ detector could consist of tracking devices, like Limited Streamer Tubes, interleaved with scintillation counters as timing and triggering devices and with thin iron plates, which act as distributed converters and also provide the return of the magnetic flux. In order to get a reasonable detection efficiency for the $\overline{n}$ the total thickness should be at least 2 nuclear interaction lengths. The time-of-flight resolution is better than 500 ps, and this should be adequate for γ/n separation over most of the energy range of the experiment.

The forward plug has the same structure as the barrel antineutron detector, with a planar geometry. A suitable configuration of the above mentioned $\overline{n}$ detector should even allow for neutron detection.

One option for a detector is to use BaBar, which fulfills all the requirements for studying multihadronic final states at these energies. However, the detection capability for low energy $\overline{n}$ and n in BaBar has to be investigated.

The alternative option of a linac-storage ring collider has also been investigated and is reported in Appendix III. Such an option can be implemented in a staged approach, with initial measurements at up to 2 GeV with a lower energy linac, and a later upgrade to higher energy and luminosity for the $2 < \sqrt{s} < 3$ GeV mass region. The two big advantages of the linac approach are: a) parasitic running during BaBar operation, thus minimizing disruption to the BaBar program; and b) much longer running time and integrated luminosity, resulting in much improved separation of the electric and magnetic form factors and the ability to do perform the additional physics topics discussed above. Recently linacs with performances suitable for a linac-storage ring collider have been built [38]. Using the LER as a storage ring for the positrons, as it is now, would mean to have a linac operating from ~ 280 MeV up to ~ 770 MeV if we want to reach the J/ψ (at least for calibration purposes).

The asymmetry of the linac-storage ring configuration would completely overcome the problem of low energy neutron detection when near threshold, being $T_n \sim 750$ MeV because of the boost. The experimental layout would be very similar to a fixed target experiment, with some special requirement for the storage ring elements downstream the interaction point to allow for detection of neutral hadrons at low angles. A less expensive and higher modularity detector with respect to the previous one can be foreseen, exploiting the smaller solid angle to be covered. A detailed study of a possible detector taking into account the floor space and other constraints in the available PEPII interaction regions has yet to be performed.

IV. RUNNING TIME REQUIREMENTS

In the following the running time for a first investigation of $e^+e^- \to N\overline{N}$ is evaluated; the goal is to study threshold and asymptotic behaviors by means of a data sample better than the present samples by at least an order of magnitude in statistical accuracy. Present data show that proton and neutron form factors are of the same order of magnitude, hence they will be measured simultaneously and with similar accuracy. These data also show a total cross section $\sigma_{tot}(e^+e^- \to N\overline{N}) \sim 1$ nb at a c.m. energy $W \sim 2$ GeV, expected to behave $\propto (1/W)^n$ with $n \sim 10$ at larger energies and $\propto \beta_N$ at lower energies down to $\sigma_{p\overline{p}}(4M^2) \sim 0.2$ nb, in the simple hypothesis $G_M \sim G_E \sim$ constant.

For a first investigation an integrated luminosity $L_{int} \sim 8\text{pb}^{-1}$ is required, under the following assumptions:

- steps of about 10 MeV, from the threshold up to $W_0 \sim 2$ GeV,
- about 200 $n\overline{n}$ events at least at each step,
- an overall efficiency $\sim 50\%$, which takes into account radiative corrections ($\sim [(W - 2M_N)/W]^B$, where B ~ 0.07), contributing an efficiency factor $\sim 70\%$ near threshold.

In this way at each step it should be possible to achieve an accuracy $\Delta G_M/G_M \sim 4\%$. The measurement of $|G_E|$ may be achieved by fitting the angular distribution; actually what is measured is p $= (\frac{|G_E|}{|G_M|})^2 \cdot \frac{4M_N^2}{Q^2}$. The accuracy on p depends on p itself and on the angular cuts. For a moderate acceptance detector we might anticipate an accuracy on $|G_E|/|G_M|$ of approximately 25 % at each point.

To measure the exponent n of the expected power law asymptotic behavior $(1/W)^n$ a trade off is needed between a measurement at the highest available energy, to have a lever arm as large as possible, and the heavy loss in statistics due to the steep drop of the form factors. Luckily enough the luminosity is expected to increase with energy. An optimal upper limit in measuring n should be around $W \sim 3$ GeV and $\Delta n \sim 0.25$, if the number of events collected at W is $N \sim 100$, corresponding to a further integrated luminosity $L_{int} \sim 8$ pb^{-1}. The total multihadronic cross section will be measured with a $\sim 1.5\%$ statistical error at $W_0 \sim 2$ GeV, with the integrated luminosity quoted above, being $\sigma_{tot}(e^+e^- \to hadrons) \sim 50$ nb. To study with the same statistical error the multihadronic cross section below the $N\overline{N}$ threshold down to $\sim$ 1.7 GeV a further integrated luminosity $L_{int} \sim 8$ pb^{-1} is needed.

In conclusion a total integrated luminosity $L_{int} \sim 24$ pb^{-1} is required to fulfill this first set of measurements, corresponding to less than two months of running time, if the average instantaneous luminosity is $L \sim 0.5 \cdot 10^{31}$ cm^{-2} s^{-1}. A two month data run might be an acceptable compromise to the BaBar program, especially if it could be synchronized with a major BaBar upgrade when the detector would not be in operation. Ultimately we would like to obtain truly definite measurements that will stand for many years to come (for example measurements of $|G_E|/|G_M|$ to 5% near threshold). This would require a much longer running time, only possible with the linac-ring collider scheme.

V. ACKNOWLEDGMENTS

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Appendix I

Nucleon timelike form factors definitions

Some comments are in order in defining the nucleon form factors in the timelike region. In the case of $e^+e^- \to N\overline{N}$ the differential cross section in the c.m. is given by:

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2 \beta C}{4Q^2}\left[|G_M|^2(1+\cos^2\theta) + \frac{4M_N^2}{Q^2}|G_E|^2 \sin^2\theta\right] \tag{1}$$

where β is the nucleon velocity in the c.m., Q^2 is the c.m. total energy squared, G_M and G_E are the magnetic and electric form factors, respectively , and they are assumed to be the analytical continuation of the form factors defined in the spacelike region. Assuming that also the Dirac form factor, $F_1 = (G_E - \frac{Q^2}{4M_N^2}G_M)/(1-\frac{Q^2}{4M_N^2})$, and the Pauli form factor, $F_2 = (G_M - G_E)/(1-\frac{Q^2}{4M_N^2})$, are analytical through the $N\overline{N}$ threshold, it must be $G_M(4M_N^2) = G_E(4M_N^2)$, i.e. exactly at threshold only the S wave is present and the angular distribution is isotropic. At very high Q^2 the contribution coming from G_E is reduced by the helicity factor $4M^2/Q^2$.

With limited statistics and limited angular acceptance, the usual wisdom up to now has been that what was achieved from the measurement of the total cross section in the timelike region is essentially $|G_M|$, which was extracted using the *ansatz* $G_E = G_M$ at all values of Q^2. One indication that this may be a poor assumption comes from recent data from TJNAF data [39] which shows the ratio G_E/G_M to be decreasing with increasing Q^2 in the spacelike region, contrary to the previously used assumption of form factor scaling. If we simply change the sign of Q^2 in the formulas for G_E in terms of F_1 and F_2, one would then predict that the ratio G_E/G_M grows from unity at threshold to values as large as 1.5 at $Q^2 \sim 9$ GeV^2 in the time-like region. On the other hand, G_E/G_M could decrease with Q^2, only a future experiment can tell.

Additional information on G_E might be obtained in the case of transversely polarized colliding beams, looking also at the ϕ distribution of the outgoing nucleon with respect to the polarization plane $\propto |G_M|^2(1-\sin^2\theta\sin^2\phi) + \frac{4M_N^2}{Q^2}|G_E|^2\sin^2\theta\sin^2\phi$. The factor

$C \sim \frac{\pi\alpha}{\beta}/(1 - e^{-\pi\alpha/\beta})$ takes into account that, at very low kinetic energy of the nucleon, Coulomb corrections modify the Born term, thus making the cross section at threshold non-zero: $\sigma(4M^2) \simeq \pi^2\alpha^3/(2M_N^2)|G_E|^2$.

Appendix II

A possible conversion of the SLAC PEP-II facility into an Asymmetric Collider for measuring Nucleon Form Factors

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Abstract

A parameter study is presented for a possible modification of the SLAC PEP-II facility into an Asymmetric Collider providing a center-of-mass energy around 2 GeV suitable for experiments to study the Nucleon form factors. Operational options for the attainable luminosity performance under different modes of operation and suggestions on the way to deal with beam energies considerably lower than the PEP-II design are discussed.

A. BASIC CRITERIA

Nucleon form factors can be studied, for example, via electron-positron collisions of the type $e^+ e^- \rightarrow N \overline{N}$.

A possible implementation of the SLAC B Factory into an asymmetric collider suitable for experiments on the internal structure of the Nucleon (PEP-III) should then envisage a collision energy E_{CM} of about 2 GeV and a non-zero center-of-mass velocity β_{CM} to improve the detection capability.

To provide a reasonable Touschek lifetime a low bunch charge density is considered leading to a very conservative value for the single-bunch luminosity $\mathcal{L}_b$. The attainable peak luminosity $\mathcal{L}$ is then given by the maximum number of colliding bunches compatible with the longitudinal bunch separation required to avoid long range beam-beam effects at each side of the interaction point (IP).

The above considerations, together with conservative assumptions for the horizontal beam-beam parameters $\xi_{x\pm}$ of both beams and for the betatron coupling κ, define the parameters of Table I. The transverse emittances $\varepsilon_{x\pm}$ are essentially defined by the CM energy, the luminosity per bunch and the optical β-functions at the IP.

The beam energies needed to provide a desired CM boost and the associated bunch charges evaluated in the hypothesis of equal beam-beam parameters for the two beams (transparency) [31] [32] are those of Table II where the energy asymmetry r_E is the ratio between the HER and the LER beam energies.

Following the experience with the PEP-II commissioning [33], a tentative PEP-III parameter list is proposed in Table III for a possible set of colliding bunches preserving enough separation in the IR to avoid long range beam-beam effects.

A $5 \times 10^{30}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ peak luminosity is quoted for 640 colliding bunches per beam i.e. for a 3.15 m (5 λ_{RF}) bunch separation, and a conservative (3%) coupling compensation.

TABLE I. Asymmetric Collider parameters

E_{CM}	$\mathcal{L}_b$	$\xi_{x\pm}$	$\beta^*_{y\pm}$	r_β	κ
GeV	$\mathrm{cm}^{-2}\mathrm{s}^{-1}$		m		
2.0	0.78×10^{28}	0.010	0.010	0.030	0.030
$\varepsilon_{x\pm}$	$\xi_{y\pm}$	$\beta^*_{x\pm}$	r	$\sigma^*_{x\pm}$	$\sigma^*_{y\pm}$
π nm rad		m		μm	μm
35.7	0.010	0.333	0.030	109.1	3.3

TABLE II. Energy asymmetry and center-of-mass velocity

r_E	β_{CM}	E_L	E_H	N_b^+	N_b^-
		GeV	GeV	10^9 e^+/bunch	10^9 e^-/bunch
1	0.00	1.000	1.000	1.60	1.60
2	0.33	0.707	1.414	2.27	1.13
3	0.50	0.577	1.732	2.77	0.92

B. OPERATIONAL CONSIDERATIONS

Two major issues deserve maximum consideration to make the PEP-II $\rightarrow$ PEP-III transition feasible.

The beam energies required to produce a 2 GeV center-of-mass energy are considerably lower that the PEP-II ones. Two possible schemes have been considered to make use of the existing magnetic structures of the two rings, outside the IR, to achieve the desired value for E_{CM}.

In the first scheme the *beams are injected at the PEP-II energies* and the magnetic fields ramped down to the operating values of each ring. For the $r_E = 2$ case of Table II the beam energy swing from the PEP-II values is of the order of 6 for the HER and 4 for the LER. Magnetic hysteresis effects are likely to modify the magnetic setting and the optical properties of the beams as, for example, the betatron tunes, will be considerably affected. The probability of losing the beams is very high when considering the large variety of magnetic elements in both structures. Even in the case of no beam loss, the reproducibility of the beam energies can be affected by the ramping-down procedure. This scheme obviously involves magnetic cycling procedures between each fill.

Another possibility is to *inject at the PEP-III energies*. This will require a re-tuning of the PEP-II injection lines, certainly less dramatic than ramping down the ring magnetic structures. It involves a reduction of the linac beam energies at the injection sections for PEP-II, possible without affecting the settings of the damping rings.

Another important issue is the IR2 layout. The present PEP-II permanent-magnet insertion is clearly not compatible with lower beam energies and must be removed when running the PEP-III experiment. A new collision scheme has to be designed, engineered and installed according to the following scenario which essentially depends on the PEP-II region where the experiment can be run **leaving** BABAR **installed in IR2**.

- If BABAR can be updated for neutron detection the experiment can be run in IR2. This requires opening the BABAR end doors to replace the PEP-II collision insertion with the PEP-III one.

- If updating BABAR involves major difficulties the PEP-III experiment should be run in another straight region (IR12 for example) which should be modified for collisions. The present IR2 interaction region would be replaced with a dummy vacuum chamber for the duration of the PEP-III experiment.

In both cases the impact on the availability of BABAR is not dramatic and the two experiments can be made compatible with a reasonable effort.

C. OUTLOOK

A feasibility study has been performed to explore the possibility of using the SLAC PEP-II facility as an Asymmetric Collider operating at a 2 GeV center-of-mass energy for the study of the Nucleon form factors.

An energy asymmetry range $r_E = 1.5 \div 2.0$ has been considered among the possible values of Table II, for center-of-mass velocities $\beta_{CM} = 0.20 \div 0.33$.

A $0.78 \times 10^{28}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ single-bunch luminosity involves reasonable bunch charges. A peak luminosity of $5 \times 10^{30}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ is anticipated with 640 colliding bunches per beam.

The impact on the existing installation of BABAR in the IR2, although requiring technical modifications to the present structures to alternatively accommodate the two experiments, does not look dramatic.

TABLE III. Parameter list for a possible Asymmetric Collider facility for the study of the Nucleon Form Factor based on PEP-II for a typical energy asymmetry range $r_E = 1.5 \div 2.0$.

Symbols / Units		**LER**	**HER**	**LER**	**HER**
E_{CM}	GeV	2.0		2.0	
r_E		1.5		2.0	
β_{CM}		0.20		0.33	
E	GeV	0.816 / e^+	1.225 / e^-	0.707 / e^+	1.414 / e^-
γ		1597	2397	1384	2768
$\kappa = \varepsilon_{yo}/\varepsilon_{xo}$		0.03		0.03	
$r_\beta = \beta^*_y/\beta^*_x$		0.03		0.03	
$r = \sigma^*_{yo}/\sigma^*_{xo}$		0.03		0.03	
$\varepsilon_{xo}\vert\varepsilon_{yo}$	π nm·rad	35.7 | 1.1		35.7 | 1.1	
$\beta^*_x\vert\beta^*_y$	m	0.333 | 0.010		0.333 | 0.010	
$\sigma^*_{xo}\vert\sigma^*_{yo}$	μm	109.1 | 3.3		109.1 | 3.3	
$\xi_x\vert\xi_y$		0.010 | 0.010		0.010 | 0.010	
f_{RF} | λ_{RF}	MHz | m	475.99903 | 0.630		475.99903 | 0.630	
f_{rev}	kHz	136.3113		136.3113	
k_b (ion gap $\sim 8\%$)		200 | 400 | 640		200 | 400 | 640	
s_b	m	10.08 | 5.04 | 3.15		10.08 | 5.04 | 3.15	
N^+_b N^-_b	e^+ e^-/bunch	1.96×10^9	1.31×10^9	2.27×10^9	1.13×10^9
I^+ I^-	mA	8.6 | 17.2 | 27.4	5.7 | 11.4 | 18.3	9.9 | 19.8 | 31.7	4.9 | 9.8 | 15.8
$\mathcal{L}_b$	cm^{-2}s^{-1}	0.78×10^{28}		0.78×10^{28}	
$\mathcal{L}$	cm^{-2}s^{-1}	$(1.6 \mid 3.2 \mid 5.0) \times 10^{30}$		$(1.6 \mid 3.2 \mid 5.0) \times 10^{30}$	

Appendix III

A linac-ring Collider Option

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A linac-ring collider has been considered in many studies as a machine capable of providing very high luminosity for Φ [34,35] or B factories [36,37]. These studies were mainly based on superconducting linac, which at that time had just progressed from the pioneering stage and none of these studies grew up to the thorough examination of a Conceptual Design Report.

It is worth noting that the design goals of such machines were very ambitious, aiming at luminosities $\mathcal{L} \approx 10^{33} \div 10^{34}$ cm^{-2} s^{-1}. In our case the required luminosity is much lower thus making the problem much simpler. Moreover, since the time of that studies the linac technology has made impressive progress, both in the basic performance parameters and in the operational reliability as proven by the realization of the TESLA Test Facility at DESY and the activities at TJNAF.

Of course a linac-ring collider implies a much bigger effort as far as the machine construction is concerned but the investment is fully exploitable by a number of research fields. Its realization can be stepped, allowing a valuable physics experiment in the first stages operating in parasitic mode during BaBar operation.

The luminosity of an asymmetric linac-storage ring collider can be simply scaled with the currents from that of PEP II, assuming that the positron beam is stored in the ring and a disposable lower energy electron beam collides in a new interaction region. The linac beam has to match the time structure and the transverse sizes of the positron beam at the interaction point. Scaling the nominal current of 1 A in the HER of PEP II, and keeping the nominal positron current of 3 A in the LER we get a luminosity $\mathcal{L} = 3 \cdot 10^{30}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ for an e^- current of 1 mA. Since the beam beam perturbation on the stored beam is 10^3

times smaller than in PEP II it is likely that an increase of luminosity can be obtained by squeezing the beam sections at the IP.

The average linac current $\approx 1\,\mathrm{mA}$ is easily achieved by CEBAF and TESLA superconducting RF cavities. The main drawback in such scheme is the very high rf power requirement and the large beam power wasting in a beam dump. The recent results from TJNAF (Jefferson Lab), where acceleration of $\approx 5\,\mathrm{mA}$ and energy recovery from the spent beam in the same cell have been achieved [38], overcome both these difficulties. The required bunch charge $n_e << 1$ nC is compatible with low e^- normalized emittance $\epsilon_n = \epsilon\beta\gamma < 10^{-6}$ m; the emittance ϵ at $\gamma \approx 500 \div 600$ is therefore comparable with the LER operational emittance allowing simple beam matching at the collision point.

The invariant mass M_{inv} produced in an asymmetric head-on collision of a linac electron beam with energy E_e and the LER with energy $E_p = 3.1$ GeV and 4.0 GeV is shown in Fig. 9. Some relevant values of M_{inv} up to the $\tau^+\tau^-$ region are shown. The curve corresponding to the HER at $E_p = 9.0$ GeV is also plotted for comparison.

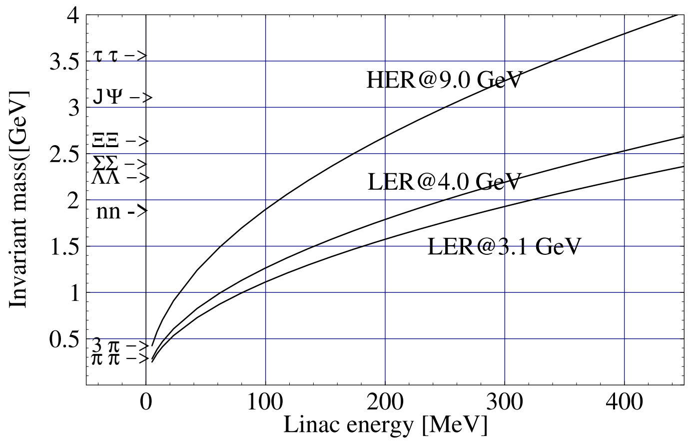

FIG. 9. $\sqrt{s}$ vs E_e in collision of linac beam against the LER @3.1GeV, LER @4.0GeV and the HER .

A step development of the linac-ring collider can be envisaged starting from just the injector. A $\approx 10 \div 20\,\mathrm{MeV}$ injector colliding with the stored beam in the LER will provide invariant mass at the threshold of $\pi^+\pi^-$ and $\pi^+\pi^-\pi^0$ production, as indicated in Fig. 9. This energy range was only marginally studied at the earliest storage rings. The low statistics of the available data on hadronic production gives the largest contribution to the error in the theoretical calculation of the muonic $g-2$ factor.

The full energy linac $\approx 300\,\mathrm{MeV}$ can provide collision at $\sqrt{s} \approx 2\,\mathrm{GeV}$ at luminosity $\mathcal{L} \approx 10^{31}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$. It is worthwhile noting that this could be done with the LER in parasitic mode owing to the smallness of the beam beam perturbation.

Operation of the PEP II rings in dedicated mode would allow higher luminosity reducing the emittance of the ring. This behavior, which apparently is contradictory to that of a standard ring collider, is due to the smallness of the beam-beam perturbation ($\xi << 0.01$) so that a large increase of the beam density at the interaction point can be obtained before the limit $\xi \approx 0.05$ is approached.

The mass range of the J/ψ family can be reached with linac energy < 300 MeV at HER operating with positron at $9\,\mathrm{GeV}$, but this option is not further considered here because it would require substantial changes in the setting of PEP II.

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