The Physics Program for PEP-N: A New Asymmetrical Electron-Positron Collider in the Regime $1.0 < \sqrt{s} < 3.1$ GeV

Mark Mandelkern*
University of California, Irvine

I discuss the physics program planned for PEP-N: A New Asymmetrical Electron-Positron Collider in the Regime $1.4 < \sqrt{s} < 3.1$ GeV.

1. Introduction

1.1. Why PEP-N?

1. There is a great deal of important physics to be done between the ϕ and the J/ψ. These region has not been explored since the early days of colliders, thus with very small integrated luminosities and relatively unsophisticated detectors.
2. By a happy coincidence, we have the opportunity to do this physics very efficiently at SLAC: due to "free" positrons from PEP-2 and the development of asymmetrical collider technology.

1.2. The Physics

1. Testing the standard electroweak model
   (a) The hadronic contribution to QED vacuum polarization-$\alpha_{em}(s)$
   (b) The hadronic contribution to $(g\text{-}2)_\mu$
   (c) Testing CVC-comparing e^+e^- annihilation to τ decay
2. Testing the quark model
   (a) Hadron structure-form factors
   (b) Vector mesons
   (c) Exotics?
3. QCD at finite momentum transfer
   (a) Light pseudoscalar meson form factors ($e^+e^- \to \gamma^* \to R\bar{R}$)
   (b) Light pseudoscalar and axial vector meson-photon transition form factors ($\gamma^*\gamma \to R$)

2. Testing the Electroweak Model

A crucial issue that has only recently attracted attention is that we cannot test the standard model without taking hadron physics into account. The parameters of the standard model can be taken as G_F, $\alpha_{em}(0)$, M_Z, M_H and the fermion masses. In order to compute physical quantities we must include radiative corrections which renormalize charges, masses and magnetic moments. Although the electroweak radiative corrections are calculable, the hadronic radiative corrections are not. However the lowest-order hadronic radiative correction can be obtained from e^+e^- annihilation data using dispersion relations.

*markm@uci.edu

2.1. α_{em}

In any of the usual renormalization schemes the conventional (on-shell) QED coupling $\alpha_{em}(s)$ can be written as:

$$\alpha_{em}(s) = \frac{\alpha_{em}(0)}{1 - \Delta\alpha_l(s) - \Delta\alpha^{(5)}_{\text{had}}(s) - \Delta\alpha_{top}(s)} \tag{1}$$

The leptonic term $\Delta\alpha_l(s)$ is accurately known. The hadronic contribution is divided so m_t can be treated as a parameter in standard model fits. The term $\Delta\alpha^{(5)}_{\text{had}}(s)$, which includes the contributions of the u through b quarks, must be determined experimentally using the dispersion relation:

$$\Delta\alpha_{\text{had}}(s) = -\frac{\alpha_{em} s}{3\pi} \int_{4\pi^2}^{\infty} \frac{R(s')}{s'(s'-s)}\, ds' \tag{2}$$

where R is the ratio of the cross section for $e^+e^- \to hadrons$ to that for $e^+e^- \to \mu^+\mu^-$, and is estimated using perturbative QCD (excluding contributions of the top quark) beyond the regime in which measurements are available. $\alpha_{em}(M_Z^2)$ is the coupling at the Z, where we determine electroweak model parameters (i.e. M_H) and/or test the standard model, and is $\sim 1/129$ compared to $\sim 1/137$ at $s = 0$ To illustrate the dependence on $\alpha_{em}(M_Z^2)$ of electroweak observables (such as M_W) we give the expression for $sin^2\theta_W$ in the NOV scheme in which the m_t and M_H dependence have been removed:

$$sin^2\theta_W(1 - sin^2\theta_W) = \frac{\pi\alpha_{em}(M_Z^2)}{\sqrt{2}G_F M_Z^2} \tag{3}$$

Based on the recent analysis of Burkhardt and Pietrzyk [1], $\Delta\alpha^{(5)}_{\text{had}}(M_Z^2) = 0.02761 \pm 0.00036$ (1.3%) corresponding to $1/\alpha^{(5)}(M_Z^2) = (1 - \Delta\alpha_l(s) - \Delta\alpha^{(5)}_{\text{had}}(s))/\alpha_{em}(0) = 128.936 \pm 0.046$ (0.037%). B&P use all available annihilation data in parameterized form. For $\sqrt{s} > 12$ GeV they use third-order perturbative QCD with $\alpha_s(M_Z^2) = 0.118 \pm 0.002$. The largest contributions to the uncertainty in $\Delta\alpha^{(5)}_{\text{had}}(s)$ are from the measured values of R in the regions $1.05 < s < 2.0$ GeV and $2.0 < s < 5.0$ GeV, each contributing about 0.8%. The latter uncertainty decreased significantly after inclusion of the BES (inclusive) data [2], even though the measurements between 2–3 GeV have large errors and potentially significant systematic uncertainties. To illustrate the sensitivity of electroweak model parameters to $\alpha_{em}(M_Z^2)$, or alternatively our ability to test the electroweak model, we consider the LEP EW WG [3] determination of $sin^2\theta^l_{\text{eff}}$ from asymmetry data and the Standard Model prediction given as a function of M_H with uncertainties due to $\Delta\alpha^{(5)}_{\text{had}}$ and m_t. The uncertainty due to $\Delta\alpha^{(5)}_{\text{had}}$ is $\sim \pm 0.0003$, which is larger than the experimental error. The overall fit to M_H from all electroweak data yields an estimate of ~ 100 GeV in which the dominant uncertainty is from $\Delta\alpha^{(5)}_{\text{had}}$.

2.2. $(g-2)_\mu$

The standard model prediction for $a_\mu \equiv (g-2)_\mu/2$ is:

$$a_\mu(\text{theory}) = a_\mu(EW) + a_\mu(\text{Had}). \tag{4}$$

$a_\mu(EW) \equiv a_\mu(QED) + a_\mu(\text{Weak})$ and is calculable to a few parts in 10^{11}. The uncertainty in a_μ is dominated by that in $a_\mu(\text{Had})$ which is usually broken up into the leading vacuum polarization contribution $a_\mu(\text{Had};1)$ of order $(\alpha/\pi)^2$, the higher order vacuum polarization contribution $a_\mu(\text{Had};2)$ of order $(\frac{\alpha}{\pi})^3$, and the hadronic light-by-light contribution $a_\mu(lol)$, also of order $(\alpha/\pi)^3$. The first of these is related to R by a dispersion relation, and the second and third must be estimated.

$$a_\mu(Had;1) = (\frac{\alpha_{em} m_\mu}{3\pi})^2 \int_{4m_\pi^2}^{\infty} \frac{ds}{s^2} K(s) R(s) \tag{5}$$

where

$$K(s) = \frac{3s}{m_\mu^2}\{x^2(1-\frac{x^2}{2}) + (1+x)^2(1+\frac{1}{x^2})\{ln(1+x) - x + \frac{x^2}{2}\} + \frac{1+x}{1-x}x^2 lnx\} \tag{6}$$

with

$$x = \frac{1-\beta}{1+\beta}, \beta = \sqrt{1-\frac{4m_\mu^2}{s}}. \tag{7}$$

Some recent analyses have used τ decay data to supplement e^+e^- data. Here CVC is used to relate processes through the vector charged weak current to comparable processes through the isovector E.M. current assuming no second class weak currents, which implies that the contribution of the axial vector current to G+ decays is zero. Thus annihilation cross sections with $G = C(-1)^I = +1$ are obtained from the rates of corresponding τ decays. While τ decay data is useful at the current level of accuracy, I-spin violation and effects such as initial and final state radiation must be understood if we are to rely on it at smaller experimental errors, as emphasized by Eidelman and Jegerlehner [4, 5]and by Melnikov [6]. PQCD is used at energies > 12 GeV. The result of Davier and Hocker [7], who use τ data, is a_μ(Had;1) = $6924(62) \times 10^{-11}$, which gives the dominant uncertainty in a_μ. The higher order hadronic vacuum polarization and hadronic *light-by-light* contribution are comparable. However while the uncertainty in the former is several parts in 10^{11}, the uncertainty in the latter is much larger. The detailed calculations done by Hayakawa and Kinoshita [8] and by Bijkens, Pallante and Prades [9] give a negative $a_\mu(LbL)$ which is of opposite sign to that obtained from the simple light quark loop calculation first done by Laporta and Remiddi [10]. Marciano and Roberts in their recent review [11]take $a_\mu(LbL) = -85(25) \times 10^{-11}$ for an overall result of $a_\mu^{SM} = 116591597(67) \times 10^{-11}$, to be compared with the BNL E821 [12] result of $116592020(160) \times 10^{-11}$ for a discrepancy of $423(173) \times 10^{-11}$. BNL E821 ultimately anticipates an uncertainty of 40×10^{-11}. Clearly we must do better on a_μ(Had;1) and $a_\mu(LbL)$ to make use of high-precision measurements of $(g-2)_\mu$.

2.3. CVC

CVC states that the charged vector weak current and the isovector electromagnetic current are members of the same I=1 multiplet. With the further assumption that no second class currents exist, (a G+ axial vector current would be second class) this implies that, modulo coupling constants, the rate for annihilation to a G+ vector state h^0 is related to that for the corresponding$\tau \to \nu_\tau h^\pm$. PEP-N covers the upper end of the τ decay range and the huge amount of data available from BABAR makes a high-precision comparison possible. One expects violations at some level from I-spin non-conservation but no 2nd class current effects have been definitively observed.

3. Hadron structure

3.1. Baryon form factors

Baryon form factors are discussed in a separate talk by Calabrese.

3.2. Meson form factors and Vector Mesons

In the quark model the lowest-lying vector mesons (ρ, ω, ϕ) are members of the $1^3S_1 q\bar{q}$ multiplet. The $\rho(1450)$, $\omega(1420)$ and $\phi(1680)$ are considered to be the 2^3S_1 radial excitations, the $\rho(1700)$ and $\omega(1650) 1^3D_1$ orbital excitations and the $\rho(2150)$ a 3^3S_1 radial excitation. There is convincing evidence for two ρ' resonances, at 1450 and 1700 MeV, 2 ω' resonances, at 1420 and 1650 MeV and a ϕ' at 1680 MeV. However there are inconsistencies in the data, poor statistics and limited energy coverage of some of these wide states. In addition, the data are not compatible with the $^3P_0$ model of meson decay, which work well for ground-state mesons. We have not found the missing ϕ.

A favored hypothesis is to include vector hybrids, $q\bar{q}g$ states which mix with the $q\bar{q}$ states. One expects such states from QCD in roughly this regime. This field is well-reviewed by Donnachie [13].

4. PQCD

Certain exclusive scattering processes involving hadrons, including electromagnetic form factors of pseudoscalar mesons, can be described accurately by perturbative QCD. The amplitudes are factored into products of hard-scattering amplitudes convolved with distribution amplitudes for the hadrons.

4.1. Pseudoscalar meson form factor

PQCD predicts the asymptotic form:

$$F_R(t) = -32\pi^2 f_R^2/(\beta_0 t ln(|t|/\lambda^2)(t \to \infty) \tag{8}$$

Here $\beta_0 = 11 - 2n_f/3$ where n_f is the number of accessible flavors. The form factor obeys an unsubtracted dispersion relation. Various approaches have been taken to calculate these form factors at low t, which are then constrained by the dispersion relation and asymptotic form. One starting point (Nakagawa et al. [14]) is approximating the low-energy behavior with resonances and using the superconvergence condition for the imaginary part of the form factor. Other approaches (Braun et al.[15]) include the methods of light-cone sum rules, chiral perturbation theory (CPT), and the constituent quark model (CQM).

4.2. Meson-photon transition form factor

This quantity is expressed in PQCD as the convolution of a perturbative hard scattering amplitude and the (non-perturbative) wave function of the meson. The form factor $F_{R\gamma^*}$ is defined through the amplitude at the $\gamma^*\gamma^*\pi$ vertex:

$$\Gamma_{\mu\nu} = -ie^2 F_{R\gamma^*}(Q^2, Q'^2)\varepsilon_{\mu\nu\alpha\beta}q^\alpha q'^\beta \tag{9}$$

where q and q' denote the spacelike photon momenta with respectively Q^2 and Q'^2. We again have an asymptotic form from PQCD:

$$F_{R\gamma^*}(Q^2, 0) = 2f_R/Q^2(Q^2 \to \infty) \tag{10}$$

and from the axial anomaly:

$$F_{R\gamma^*}(0, 0) = 1/(4\pi^2 f_R) \tag{11}$$

Diehl et al. [16] show that the form factor is independent of the shape of the meson distribution amplitude over a wide kinematical range.

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