33

High Intensity Electron and Positron Beams

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33.1 Overview

This report addresses the following questions:

1) What accelerator capabilities at heavy flavor factories are required to realize the full range of physics opportunities?

2) What are new physics opportunities using high power electron and positron beams?

Regarding the first question, two types of flavor factories are being constructed or proposed in the world. (See Section 33.2.) SuperKEKB, a super-high luminosity B factory, is under construction in Japan, and super tau-charm factories have been proposed in Italy and Russia (and considered in China). US involvement with SuperKEKB has contributed to significant advances in areas critical to the success of that project. The US is strongly urged to support SLAC, Wayne State, U. Hawaii and other institutions to to collaborate with the accelerator division of KEK to maximize the luminosity achieved at SuperKEKB, and to bring new capabilities to the project. Such collaboration on the accelerator side would also complement and benefit the collaboration on the detector (Belle-II) side. An ICFA workshop on commissioning of SuperKEKB and other electron-positron colliders will be held in November, 2013.

Three plans or proposals are discussed in response to the second question:

The DarkLight experiment plans to use the high-intensity electron beam of the JLab FEL, impinging on a hydrogen target, to search for gauge bosons associated with Dark Forces theories. (See Section 33.3.1.)

Another group proposes a search for dark matter in the MeV - GeV range that would utilize a high-intensity electron beam. (See Section 33.3.2.)

It is also proposed to use a high-intensity, low-emittance positron beam, impinging on a plasma target, to generate muon/anti-muon pairs. If yields can prove sufficient, such an approach holds out the prospect of providing source beam for a future muon collider without the need for a separate muon cooling stage. The possibility of a proof-of-principle study at SLAC is raised. This proposal is discussed in Section 33.4.

Parameter	KEKB Design LER/HER	KEKB Actual LER/HER	SuperKEKB LER/HER	Units
Beam energy E	3.5/8	3.5/8	4/7	GeV
Hor. emittance ϵ_x	18/18	18/24	3.2/5.1	nm-rad
Vert. focusing β_y^*	10/10	5.9/5.9	0.27/0.30	mm
Vert. size at IP σ_y^*	1900	940	48/62	nm
Beam-beam param. ξ_y	0.052	0.129/0.090	0.09/0.09	
Bunch length σ_z	4	$\tilde{6}$	6/5	mm
Beam current I	2.6/1.1	1.64/1.19	3.6/2.6	A
Number of bunches N	5000	1584	2500	
Luminosity L	1	2.1	80	$10^{34} cm^{-2} s^{-1}$

Table 33-1. *Key machine parameters for SuperKEKB and its predecessor, KEKB.*

33.2 Flavor Factories

33.2.1 SuperKEKB

SuperKEKB, an upgrade to the KEKB B-factory, is under currently under construction in Japan, with commissioning scheduled to commence in January, 2015. To achieve the target luminosity of $8 \times 10^{35} cm^{-2} s^{-1}$ will be a tremendous challenge, which will benefit greatly from contributions from the US and elsewhere.

To achieve this luminosity, which represents a 40-fold increase over that of KEKB, SuperKEKB will employ beam currents approximately twice as high as those used at KEKB, and vertical bunch sizes at the collision point about 20 times smaller than those achieved at KEKB. The main machine parameters are shown in Table 33-1.

Although it may be premature to contemplate increases in the design luminosity of a machine that has not yet started commissioning, we will first present physics motivations for increasing luminosity beyond the design luminosity, followed by discussions of current efforts to maximize the luminosity achievable with the design that is currently under construction. We will also discuss the physics justifications and technical feasibility of adding polarized beam(s) to SuperKEKB.

33.2.1.1 Physics motivation for an even higher luminosity B Factory

Here we discuss the physics reach of a machine that extends the capability of a Super-B factory and achieves a luminosity of 1×10^{37} cm^2/sec. We assume that it will integrate 500 ab^{-1} during a long running period (and hence accumulates a data sample ten times larger than that expected at a Super-B factory).

The high luminosity Super-B factory has two advantages compared to hadronic machines: the relative cleanliness of the initial state (at the $\Upsilon(4S)$ resonance, a pair of B mesons is produced with no other accompanying particles) and the CP-entangled nature of the coherent initial state. Both features are used extensively to enhance the physics reach of the facility. We assume that the high luminosity, 10^{37}/cm^2/sec, Super-B factory operates on either $\Upsilon(4S)$ resonance to study B physics or else on the $\Upsilon(5S)$ resonance to investigate B_s decays.

A higher luminosity Super B factory may focus more effort on rare process involving D mesons and τ leptons. It should be noted that these investigations do not require running on the $\Upsilon(4S)$ resonance: the statistics of the $\Upsilon(5S)$ or continuum data taking also contribute equally.

For some loop processes, especially those that are highly suppressed by a one factor of λ compared to $b \to s$ penguins, the statistics of the upcoming Super B factory will not be sufficient to explore new physics and reach the current limits of theoretical understanding. An example would be time-dependent CP violation in the $b \to d$ process $B^0 \to K^0\bar{K}^0$. Here there are two complex phases: one from the $B^{-}\bar{B}$ mixing in the box diagram and the other from top-down quark coupling in the $b \to d$ penguin loop. If new physics is absent, there should be a clean cancellation and no time-dependent CP violation should observed. To measure time-dependent CP violation for this mode requires vertexing both the long-lived K_S mesons in the silicon vertex tracking systems of the detector (and hence these modes may be difficult at a hadron collider experiment at the LHC). Extrapolating from the B Factories, we expect a sensitivity of order $\mathcal{O}(0.02)$ on the sine-like CP violation parameter S with the full 500 ab^{-1} sample.

With the 500 ab^{-1} sample, one should be able to explore the full range of all $b \to d$ penguin loops. Other important examples are searches for right-handed currents from NP. The two favored modes are the self-conjugate $b \to s$ radiative penguin modes such as $B \to K^{*0}\gamma \to K_S^0\pi^0\gamma$ and $B \to K_S\phi\gamma$. Expected sensitivities are $\mathcal{O}(0.01)$ and $\mathcal{O}(0.04)$, respectively for the effective S parameter at 500 ab^{-1}. These sensitivities will approach the expected corrections from the SM. Conversely, it may be possible to find the effects of NP right-handed currents.

The Super B factory at 50 ab^{-1} will observe the first signals for $B \to K\nu\bar{\nu}$ and $B \to K^*\nu\bar{\nu}$ but will not be able to make precise measurements. This is similar to the program for rare kaon decays. These modes could be important for constraining NP. The good background conditions and detector capabilities of the Super B Factory must be maintained to measure these "missing energy" modes at even higher luminosities.

The use of full reconstruction tagging is critical to measuring B-decays to invisible final states. In addition to $B \to K(*)\nu\bar{\nu}$, there are a number of other processes, including $B \to$ missing energy (tagged by B's "on the other side"), $B \to \gamma +$ missing energy, $B \to l\nu +$ missing energy. Those processes constrain not only possible heavy new physics states in the $b \to s(d)\nu\bar{\nu}$ vertex (where the "missing energy" is neutrinos), as well as light Dark Matter (e.g., see the models described in [1, 2, 3, 4]).

The Super-B factory is able to make many important measurements with fully reconstructed "tagged" B mesons despite the relatively low product of efficiency and branching fraction ($\sim 0.5\%$) for reconstructing the accompanying B meson. This capability is often described as being equivalent to providing a "single B meson beam". At a high luminosity Super B factory, this capability can be extended to a "single B meson beam with CP-tagged initial states". These entangled final states could give pristine measurements of γ, lifetime differences and other weak interaction parameters (examples are described in [5]).

Currently, signals have been observed by B factories and hadron colliders for $D - \bar{D}$ mixing. The signals for $y = \Delta\Gamma/2\Gamma$ are clear. There are no statistically significant signals for $x = \Delta m/\Gamma$ yet. We assume that a non-zero x signal will be established by the Super B factories or LHCb. This will allow the program of constraining CP violation associated with D mixing, which is very small in the SM. The sensitivity to arg(q/p), the phase of the D mixing measurement could reach the 0.5^0 level or below with a 500 ab^{-1} data sample.

The possibility of observing τ lepton flavor violating decays is very interesting and could be revolutionary. The sensitivity of a Super B factory or higher luminosity e^+e^- machine is especially interesting if NP in the charged lepton sector has strongly mass-dependent couplings.

New physics models could enhance a variety of τ LFV modes: $\tau \to \mu\gamma$ is one notable example but $\tau \to \eta^{'}\mu$ or $\tau \to \pi^+\pi^-\mu(e)$ are also possible. At high luminosity e^+e^- facilities one can explore the full range of these possibilities. So far LHCb has reported limits on the all charged final state $\tau \to \mu^+\mu^-\mu^+$ only.

The sensitivity to one of the benchmark modes $\tau \to \mu\gamma$ depends on what is assumed for luminosity scaling. For example, a $\sqrt(L)$ background-dominated scaling gives a sensitivity of 1×10^{-9} at 500 ab^{-1} while a linear luminosity scaling gives 0.3×10^{-9} at 500 ab^{-1}, a factor of ten beyond the level of a Super B factory. Since background from ISR (Initial State Radiation) processes such as $e^+e- \to \gamma\tau^+\tau^-$ is present, additional tools to suppress the background may be required to reach the ultimate sensitivity. One possibility is the use of polarized beams. This together with the high luminosity would provide a compelling τ LFV program.

Finally, the possibility of CP violation in τ decay will be examined further. The sensitivity for the parameter $Im(\eta_s)$ determined from CP violation searches using angular correlations in $\tau^\pm \to K_S\pi^\pm\nu$ is currently ~ 0.036 and could reach the ~ 0.0015 level with 500 ab^{-1} if no limiting systematic effects are found.

33.2.1.2 US contributions to SuperKEKB

The design, construction and commissioning of the SuperKEKB e^+e^- collider at the KEK laboratory in Tsukuba, Japan, is of strong interest to the US particle physics and accelerator communities. The US particle physics community is participating in the BELLE-II detector. SLAC and several other laboratories and universities are contributing to the accelerator. The SLAC Accelerator Directorate would like to enlarge this accelerator participation over the years as funding allows. The present activities include those in the US-Japan yearly agreement and those discussed with the DOE OHEP. The activities were chosen to help produce luminosity sooner in SuperKEKB, to reach higher luminosity, and to match SLAC interests.

Current activities at SLAC:

Construction of transverse deflecting cavity for linac longitudinal beam diagnostics (completed).

Bunch-by-bunch feedback studies of instability control of multiple bunches in SuperKEKB. Overall design, feedback theory, electronics design, and software are involved.

Positron flux concentrator. The design of the flux concentrator for SuperKEKB is modeled on the design used in the SLC and PEP-II. Construction advice is ongoing.

Beam dynamics studies. SLAC is working on the beam-beam effect and Coherent Synchrotron Radiation (CSR) related to colliding beam; both are applicable to other storage rings.

Interaction point feedback. SLAC is helping to design the feedback system to keep the beams in collision at the IP. Theoretical studies of collision feedback are being done. IP optics is being studied for optimal feedback. SLAC is constructing the magnetic dither coils for acting on the two beams.

Interaction region design. Studies and consultation on the design and layout of the interaction region are ongoing including magnets, vacuum chambers, backgrounds, masking, collimation, magnetic field harmonics, lost particles, x-ray production, and synchrotron radiation.

Development of a high-energy pixelized detector for the next generation bunch-by-bunch x-ray beam diagnostics needed to measure the low-emittance bunch sizes.

Potential future activities at SLAC:

Commissioning. SLAC accelerator physicists would like to participate in SuperKEKB ring commissioning, positron damping ring commissioning, and linac low emittance tuning.

Expanded role in the IP feedback to include power amplifiers, control circuitry, and optimized algorithms.

High precision alignment of the rings and linac.

Beam dynamics studies of the fast ion instability, very low emittance generation, and beam-beam tail generation.

The luminosity monitor design. The luminosity monitor is important for providing feedback on the alignment of the opposing colliding beams and has to work at a very high readout rate.

Collimator design. SuperKEKB is looking into improved collimator designs. The collimator designs for PEP-II are of potential interest for the SuperKEKB project.

Beam energy monitor using inverse Compton scattering of laser photons.

Significant contributions have also come from other US institutions. For example:

Wayne State University is constructing a beamstrahlung monitor, which is a collision quality diagnostic using the synchrotron-like light that is generated by beam-beam deflections, and which can be used to directly diagnose size and position mismatches between the two colliding beams. This is expected to play in important role in collision tuning for maximizing the luminosity.

The University of Hawaii is constructing a high-speed digitizer and readout system for the bunch-by-bunch x-ray beam size monitor, which is needed to measure the profiles of the low-emittance bunches.

The CesrTA experiment at Cornell University has been collaborating in the testing of x-ray optics elements (including resolution measurements and high-power burn tests of x-ray optics proposed for use at SuperKEKB), and in studies of electron-cloud mitigation techniques. It has also carried out extensive studies of electron-cloud-induced beam dynamics, intra-beam scattering and low-emittance tuning.

BNLis constructing a solenoid compensation coil for use in the SuperKEKB interaction region.

Fermilab is collaborating in the testing of electron-cloud mitigation coatings.

Further collaborations on issues of concern to the success of SuperKEKB are eagerly anticipated.

33.2.1.3 Physics with Polarization at SuperKEKB: Neutral Current Electroweak Physics, τ EDM, τ g-2

With its ultra-high luminosity SuperKEKB, if equipped with polarization, would uniquely be in a position to probe new physics in a manner inaccessible to any other currently approved machine. In particular, the polarization of the electron beam enables SuperKEKB to measure the weak neutral current vector coupling constants of the b-quark, c-quark and muon at significantly higher precision than any previous experiment. The precision of the vector coupling to the tau and electron will be measured with a precision comparable to that attained at SLC and LEP. Within the framework of the Standard Model these measurements of g_V^f can be used to determine the weak mixing angle, θ_W, through the relation: $g_V^f = T_3^f - 2Q_f \sin^2\theta_W$, where T_3^f is the 3rd component of weak isospin of fermion f, Q_f is its electric charge in units of electron charge and where higher order corrections have been ignored here for simplicity.

A polarized SuperKEKB would determine g_V^f by measuring the left-right asymmetry, A_{LR}^f, for each identified final-state fermion-pair in the process $e^+e^- \to f\bar{f}$.

$$A_{LR}^f = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} = \frac{sG_F}{\sqrt{2}\pi\alpha Q_f} g_A^e g_V^f < Pol > \tag{33.1}$$

where g_V^e is the neutral current axial coupling of the electron, $g_A^f = T_3^f$, G_F is the Fermi coupling constant, s is the square of the centre-of-mass energy, and $< Pol >= 0.5\{\left(\frac{N_{eR}-N_{eL}}{N_{eR}+N_{eL}}\right)_{Right\ Pol.\ Beam} - \left(\frac{N_{eR}-N_{eL}}{N_{eR}+N_{eL}}\right)_{Left\ Pol.\ Beam}\}$, is the average beam polarization.

These asymmetries arise from $\gamma - Z$ interference and although the Standard Model asymmetries are small (-3×10^{-4} for the leptons, -3×10^{-3} for charm and -1.3% for the b-quarks), the unprecidented precision is possible because of the high luminosity of SuperKEKB together with a 70% beam polarisation measured to $\pm0.5\%$. To achieve the required precision all detector-related systematic errors are made to cancel by flipping the polarization from R to L in a random, but known, pattern through a run. $< Pol >$ is measured with both a Compton Polarimeter, which has an uncertainty at the interaction point of $< 1\%$ and by measuring the forward-backward polarization asymmetry of the tau-pairs using the kinemetic distributions of the decay products of the tau. The latter can be used to determine $< Pol >$ to 0.5% in a manner entirely independent of the Compton Polarimeter.

With 30 ab^{-1} of data having 70% electron beam polarization, SuperKEKB can provide a measurement of $\sin^2\theta_W$ with a precision of 0.00036 at 10 GeV using only tau-pairs and muon-pairs, which is comparable to the most precise measurement of $\sin^2\theta_W$ by a single experiment, performed at Z^0-pole with SLC. Being at a lower energy, this measurement will provide a probe of the running of the couplings with unprecidented precision. Perhaps more interestingly, the 3σ discrepancy between the LEP measurements of the right-handed b-quark couplings to the Z would be experimentally probed with higher precision at a 70% polarized SuperKEKB with 30 ab^{-1}. Also, measurements with the projected precision will enable SuperKEKB to probe parity violation induced by the exchange of heavy particles such as Z-boson or hypothetical TeV-scale Z' boson(s). If such bosons only couple to leptons they will not be produced at the LHC. Moreover, a polarized SuperKEKB machine would have a unique possibility to probe parity violation in the lepton sector mediated by light and very weakly coupled particles often referred to as "dark forces". Recently, such forces have been entertained as a possible connecting link between SuperKEKB and dark matter [6, 7]. The enhancement of parity violation in the muon sector has been an automatic consequence of some models [8] that aim at explaining the unexpected result for the recent Lamb shift measurement in muonic hydrogen [9]. The left-right asymmetry of the $e^-e^+ \to \mu^-\mu^+$ in such models is expected to be enhanced at low-to-intermediate energies, and a polarized SuperKEKB facility may provide a conclusive test of such models, as well as impose new constraints on parity-violating dark sector.

Measurements on τ leptons at the intensity frontier provide a powerful tool to search for New Physics effects in a way that is competitive and complementary with respect to LHC and other existing or planned experiments like MEG and Mu2e. Lepton Flavor violation in τ decay is a measurable unambiguous signal for many New Physics models, and the expected sensitivities of SuperKEKB is unrivaled. The large and clean dataset of $e^+e^- \to \tau^+\tau^-$ events will also permit additional New Physics searches based on precision measurements of CP violation in τ decays, and of the τ $g-2$ and EDM form factors, with impressive improvements on the present experimental accuracy. Furthermore, if polarization is added to SuperKEKB, there would be an additional ability to identify sources of New Physics in Lepton Flavour Violation (being able to distinguish between left-handed and right-handed new physics currents) and to significantly improve the experimental precision on the τ $g{-}2$ and EDM form factors [10].

33.2.1.4 Polarization in electron storage rings

Spin-polarized electron beams would add a significant extension in reach to the physics program of SuperKEKB. The physics case is made in Sec. 33.2.1.3; here we will explore the accelerator aspect of this upgrade.

Engaging in a project to upgrade SuperKEKB to polarization capability would match capabilities and experience at SLAC, BNL and JLab. It would be an interesting, challenging project from the accelerator point of view. There would be synergies with ILC work at several levels (source, spin manipulation, polarimetry) as well as muoncollider work. Being of significant scope it would be an obvious candidate for a collaboration between several US National Labs and foreign laboratories.

In the context of B-Factories, specifically SuperKEKB, Sokolov-Ternov polarization is quickly shown to have a time scale of several hours, long compared to the anticipated beam lifetime, and not a viable option. Polarization in SuperKEKB will involve preparing and injecting a beam of polarized electrons in the correct spin orientation parallel to the local precession axis at the injection point. While polarized sources with the required intensity exist (e.g., the SLC polarized gun), low-emittance polarized sources may not readily be available. BNL has developed such a gun which is presently being readied for commissioning. It needs to be assessed whether e.g. the CEBAF polarized gun (or other existing ones) may have sufficient parameters, or whether the BNL gun research can be advanced to produce a suitable gun. The alternative would be to use a polarized dc-gun followed by a damping ring. A Wien filter is typically used to prepare the polarization state. Being single path, the beam transport from the source through the linac to the storage ring will not significantly reduce the degree of polarization.

In order to prepare the helicity state needed at the detector, spin rotators are necessary in the storage ring. A straight-forward scheme rotates the polarization vector in to the longitudinal plane upstream of the detector and back vertical downstream. Such schemes were designed in concept for the Italian SuperB project and shown to be able to provide long enough polarization time to provide up to 70% polarization on average. The challenge in the SuperKEKB context is to find space in the machine and the optical match to the magnet lattice. The rotators themselves would consist of 36.6 Tm of solenoid to rotate the polarization vector by 90 deg followed by 5.7 deg of horizontal bending to convert the radial polarization into longitudinal, plus an array of at least 5 quadrupoles to compensate for the plane rotation caused by the solenoid. The bending is part of the overall 360 deg bending of the ring. Dipole-rotators were used at HERA but cause too large vertical beam offsets at the lower energy which would cause significant vertical emittance growth. Working out the optics for this is another challenge to be met.

It can be shown that any practical scheme with solenoid rotators (i.e. a scheme avoiding reverse bending magnets) is mismatched in spin motion and therefore incurs strong depolarization near integer values of the spin tune. This forces the beam energy to be such that the spin tune is near 0.5 and thus quantizes the energy of the electron beam in steps of 0.441 GeV. The spin rotators add 0.5 units to the spin tune, therefore it appears that 7 GeV is not a bad operating energy for a polarized SuperKEKB HER. The effect of the mismatch due to the spin rotators can be mitigated by adding a second spin-rotating solenoid with 180 deg spin rotation at the opposite azimuth in the ring (and changing polarity of one of the rotator solenoids near the IP). In this way the spin tune can be shown to be fixed near 0.5 independent of the beam energy and resonant depolarization is highly suppressed. Such a scheme was investigated for possible use in LEP. It would make polarization only weakly dependent on machine alignment and have the additional property of being symmetric w.r.t. the sign of the polarization, i.e. fast spin flips even on a bunch-by-bunch time scale are feasible provided the source can be keyed in this way. Without the second solenoid, while different polarities of polarization are still possible they would not be symmetric; one state would decay much faster than the other. In addition, a high degree of polarization would require stringent orbit control although the low emittance already requires that to a certain degree. For a source of 80% polarization, an average polarization of 70% seems achievable.

At lower beam energy–i.e. in a τ-Charm Factory–the argumentation is fundamentally the same although the time scale may change as it depends on the 5^{th} power of the relativistic beam energy γ. In a recent τ-Charm workshop it was indicated that 67% polarization at 2 GeV may be possible using a similar scheme as outlined here for SuperKEKB.[11] Since the rotator solenoids scale with beam energy the amount of extra space needed remains to lowest order the same relative to the total machine length. A potentially interesting variant of this scheme increases the energy bandwidth by splitting each solenoid in two with interleaved bending (with certain conditions for the angles involved).

A highly accurate Compton polarimeter near the detector would complete the facilities needed. It may be of significant benefit for machine operation and tuning to have a second, less accurate but faster, polarimeter at a different location in the ring.

An important question is the effect of the spin rotators on machine luminosity. Fundamentally, the impact of the solenoid rotators should be small. The performance of the modified optics will need to be studied in detail to assess any impact. An interesting case is the effect of the beam-beam interaction on polarization; this is not well known at present (HERA saw some impact, partially compensable by machine tuning).

Engaging in a project to upgrade SuperKEKB to polarization capability would match capabilities and experience at SLAC, BNL and JLab. It would be an interesting, challenging project adding a unique capability to SuperKEKB and advancing the state of the art. There would be synergies with ILC work at several levels (source, spin manipulation, polarimetry) as well as muon-collider work. Being of significant scope it would be an obvious candidate for a collaboration between several US National Labs and foreign laboratories.

33.2.2 Super Tau-Charm Factories

Two designs for tau-charm factories are currently being actively proposed, one at Frascati (Tor Vergata) in Italy[12], and one at Novosibirsk in Russia[13]. Both machines are two-ring, symmetric-energy machines, with provisions for longitudinally polarized beams. A summary of the preliminary main parameters of the two designs is given in Table 33-2. Parameters are given for nominal center-of-mass energies of 4 GeV, but both designs are tunable down to 1 GeV.

Note that it has also been considered to build a tau-charm factory at IHEP in Beijing, though it is not apparently an active proposal as of yet.

Parameter	Super τ/charm (Tor Vergata)	Super Phi-Tau-Charm (Novosibirsk)	Units
Center-of-mass energy E_{CM}	4	4	GeV
Circumference C	330	368 (VEPP-4 tunnel)	m
Crossing angle (full)	60	60	mrad
Beam-beam tune shift ξ_y	0.097	0.095	
Beta function at IP β_x/β_y	13/0.06	20/0.06	cm
Emittance η_x/η_y (w/IBS)	2.6/0.065	3.1/0.016	nm-rad
Bunch length σ_z	8	8	mm
Beam current I	1.58	1.8	A
Number of Bunches N	513	418	
Luminosity L	1	1	$10^{35} cm^{-2} s^{-1}$

Table 33-2. *Preliminary machine parameters for Super τ/charm (tor Vergata)[12] Super Phi-Tau-Charm (Novosibirsk)[13] proposals.*

33.3 New applications for high-power electron beams

33.3.1 The DarkLight Experiment

DarkLight will study the production of gauge bosons associated with Dark Forces theories in the scattering of 100 MeV electrons on proton a target. DarkLight is a spectrometer to measure all the final state particles in $e^- + p \to e^- + p + e^- + e^+$. QED allows this process and the invariant mass distribution of the e^+e^- pair is a continuum from nearly zero to nearly the electron beam energy. Dark Forces theories, which allow the dark matter mass scale to be over 1 TeV, predict a gauge boson A' in the mass range of 10-1,000 MeV and decays to an electron-positron pair with an invariant mass of $m_{A'}$. The DarkLight experiment aims to search for this process using the 100 MeV, 10 mA electron beam at the JLab Free Electron Laser impinging on a hydrogen target with a 10^{19}cm^{-2} density. The resulting luminosity of $6{\times}10^{35}$/cm^2-s gives the experiment enough sensitivity to probe A' couplings of $10^{-9}\alpha$. DarkLight is unique in its design to detect all four particles in the final state. The leptons will be measured in a large high-rate TPC and a silicon sensor will measure the protons. A 0.5 T solenoidal magnetic field provides the momentum resolution and focusses the copious Møller scattering background down the beam line, away from the detectors. A first beam test has shown the FEL beam is compatible with the target design and that the hall backgrounds are manageable. The experiment has been approved by Jefferson Lab for first running in 2017.

33.3.2 Dark matter searches in MeV-GeV range

High intensity electron beams are also instrumental in proposed fixed target searches for light, weakly coupled particles including dark matter in the MeV - GeV range [14]. The basic setup involves $1020 - 23$ electrons on target with energies of ~ 1 GeV or higher striking stationary nuclei in a beam dump. These collisions can efficiently produce new weakly interacting states, which pass through shielding material and scatter 10s of meters downstream in a cubic-meter scale (or smaller) detector. For electron sources, beam related backgrounds from neutrinos and fast neutrons are typically negligible, so these experiments can operate on a small scale with high acceptances for new particles in the MeV - GeV mass range. The dominant beam unrelated backgrounds are from cosmogenic neutrons with a flux of $\sim 10^{-2} m^{-2}$ Hz at ~ 10 m.w.e. depths. With a continuous wave beam, this typically requires some shielding around the detector (e.g. a neutron moderator). However, a pulsed beam with a duty cycle of $10^{-4} - 10^{-3}$ or smaller takes full advantage of the electron fixed target approach by reducing live time and thereby eliminating cosmogenic backgrounds to allow for unprecedented sensitivity in this mass range.

33.4 New application for high-power positron beams: Muon production from positron beam interaction on a plasma target

33.4.1 Introduction

Muon beams are customary obtained via K/π decays produced in proton interaction on target. Their use in high energy physics experiments has continous increasing interest for rare decays experiments, precision measurement experiments, for neutrino physics, and for muon colliders feasibility studies. Several dedicated experiments are ongoing to produce high intensity muon beams with low emittance. In this paper we will investigate the possibility to produce low emittance muon beams from electron positron collisions at centre-of-mass energy just above the $\mu^+\mu^-$ production threshold with maximal beam energy asymmetry – i.e. a ≈ 45 GeV positron beam interacting on an electron target . The large boost, $\gamma \approx 200$, of the centre-of-mass allows the final state muons to be very collimated, the muons to be produced with high energy with an average laboratory lifetime of about 500 μs, and a minor degradation of the positron beam emittance from bhabha scattering. The value of the $e^+e^- \to \mu^+\mu^-$ cross section, about 1 μb just above threshold, requires a target with very high electron density, on the order of 10^{20} electrons/cm^{-3} to obtain an reasonable muon production efficiency. Such and high density can be obtained in a plasma excited via a synchronized electron beam.

33.4.2 Processes at $\sqrt{s}$ around 0.212 GeV

The dominant processes at $\sqrt{s}$ around 0.212 GeV are bhabha scattering, $\mu^+\mu^-$ production, and $\gamma\gamma$ scattering. These processes have been simulated with the BabaYaga event generator [15], with the exception of collinear radiative bhabha scattering, simulated with BBBrem [16]. $\gamma\gamma$ scattering will not be discussed in detail, having a cross section that is, in the end, smaller than that for $\mu^+\mu^-$ production.

33.4.2.1 $e^+e^- \to \mu^+\mu^-$ characteristics

The cross section for continuum muon pair production $e^+e^- \to \mu^+\mu^-$ just above threshold is the Born cross section enhanced by the Sommerfeld-Schwinger-Sakharov (SSS) threshold Coulomb resummation factor [17]. The value of cross section for the process $e^+e^- \to \mu^+\mu^-$ is shown in Figure 33-1 as a function of the centre-of-mass energy. The values obtained from the from the Born level formula and that enhanced by the SSS are shown. It approaches its maximum value of $\approx 1\mu$b at $\sqrt{s} \approx 0.230$ GeV.

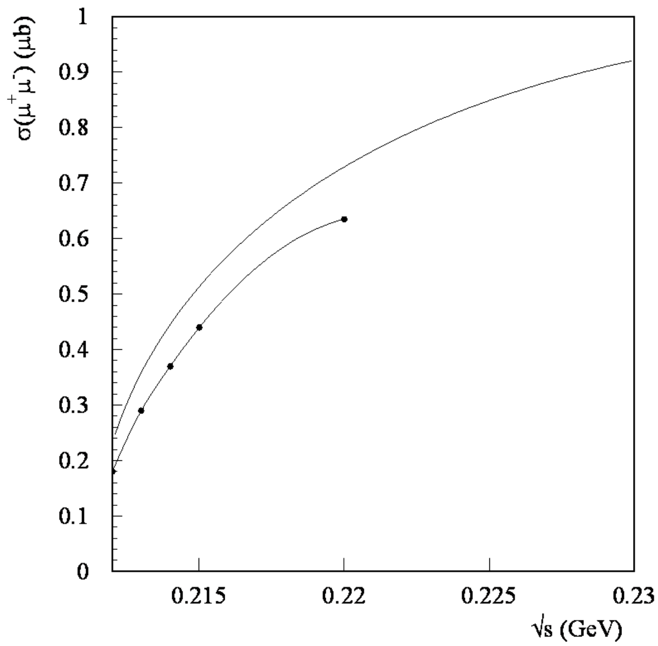

Figure 33-1. *$e^+e^- \to \mu^+\mu^-$ production cross section around threshold.*

In our scheme these values of $\sqrt{s}$ can be obtained from fixed-target interacions with a positron beam energy $E_+ \approx s/(2m_e) \approx 45$ GeV, where m_e is the electron mass with a boost $\gamma \approx E_+/\sqrt{s} \approx \sqrt{s}/(2m_e) \approx 220$. The scattering angle θ_μ of the outcoming muons has a maximum value for muons emitted in the rest frame orthogonally to the positron beam, so its value depends on $\sqrt{s}$. In the approximation $\beta_\mu = 1$, where β_μ is the muon velocity, one can easily obtain for the maximum scattering angle $\theta_\mu^{max} = 4m_e(s/4 - m_\mu)^{1/2}/s$. Its value increases with $\sqrt{s}$ with approximately the same shape as the $\mu^+\mu^-$ production cross-section. The difference between the maximum and the minimum muon energy ΔE_μ, also depends on $\sqrt{s}$, with the $\beta_\mu = 1$ approximation $\Delta E_\mu = \sqrt{s}/(2m_e)(s/4 - m_\mu^2)^{1/2}$. These values have to be folded with the muon angular distribution in the rest frame $(1 + \cos\theta_\mu^{*2})$. The value of $\sqrt{s}$ has to be optimized to maximize the $\mu^+\mu^-$ production and to minimize the beam angular divergence and energy spread. The θ_μ distribution obtained with the BabaYaga generator is shown in Figure 33-2 for different $\sqrt{s}$ values. Muons produced with very small momentum in the rest frame are well contained in a cone of $\approx 5 \times 10^{-4}$ rad for $\sqrt{s} = 0.212$ GeV, the cone size increases to $\approx 1.2 \times 10^{-4}$ rad at $\sqrt{s} = 0.220$ GeV. Similarly, the energy distribution of the muons, shown in Figure 33-2, has an rms that increases with $\sqrt{s}$, from about 1 GeV at $\sqrt{s} = 0.212$ GeV to ≈ 3 GeV at $\sqrt{s} = 0.220$ GeV.

It is also possible to produce muonium below the $\mu^+\mu^-$ threshold that can be eventually dissociated in the interaction with the plasma. It has been studied in [17]. The e^+e^- width is proportional to $1/n$ where n indicates the muonium energy level [17]. The cross section of the S^1 state in the narrow width approximation is about $10^{-9} mb E_+/\sigma_{E_+}$, where σ_{E_+} is the positron beam energy spread. This value renders unrealistic the use of this process for copious muon production.

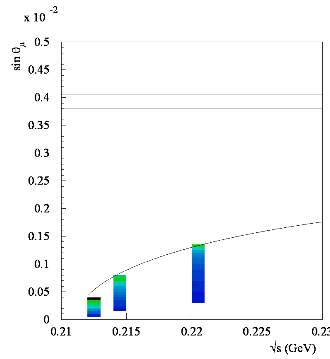

Figure 33-2. *Muon scattering angle distribution as a function of $\sqrt{s}$.*

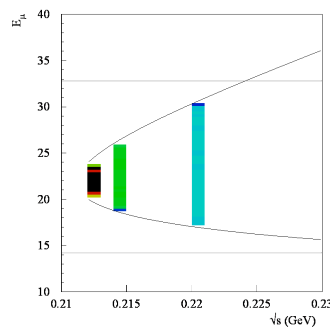

Figure 33-3. *Muon energy distribution as a function of $\sqrt{s}$.*

33.4.2.2 $e^+e^- \to e^+e^-\gamma$ characteristics

The bhabha scattering represents the largest source of beam loss in this study, setting an upper limit on the ”conversion efficiency.” The large angle $e^+e^- \to e^+e^-\gamma$ process has been simulated in the rest frame using BabaYaga with radiative photon energy, $E^*_\gamma < 10$ MeV, and a scattering angle $\theta_\gamma > 10\,\text{deg}$. The total cross section in the region of $\sqrt{s} = 0.2$ GeV is $\sigma_{bha} \approx 0.6$ mb.

As expected, the process proceeds via t-channel and most of the generated events are produced at very small positron scattering angle θ_+. Figure 33-4 shows the distribution of scattering angle as a function of the scattered positron energy for a positron beam energy $E_+ = 46$ GeV.

The distribution indicates that the beam loss due to this process can be substantially decreased with reasonable acceptances.

Collinear radiative bhabha scattering are simulated with BBBrem [16]. The total cross section is about 150 mb for a $E_\gamma > 0.01E_+$ and it gets about 60 mb for $E_\gamma > 0.1E_+$. This process will actually set a limit to the positron beam effectiveness as it sets limits to the beam lifetime in high luminosity $e\ +\ e^-$ colliders.

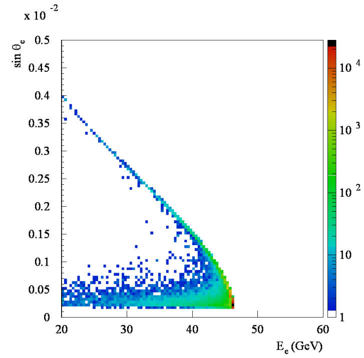

Figure 33-4. *Distribution of scattering angle as a function of scattered positron energy for a positron beam energy $E_+ = 46$ GeV.*

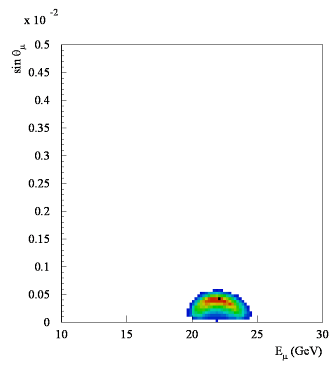

Figure 33-5. *Scattering angle vs muon energy distribution for the $\sqrt{s} = 0.212$ GeV case.*

33.4.2.3 Working with numbers

The number of $\mu^+\mu^-$ pairs produced per interaction is $n(\mu^+\mu^-) = n^+\rho^- L\sigma(\mu^+\mu^-)$, where n^+ is the number of positrons in the beam, ρ is the electron density in the plasma, L is the length of the plasma target, and $\sigma(\mu^+\mu^-)$ is the muon pair production cross section. As described in the previous sections, the dominant process at these energies is collinear radiative bhabha scattering with a cross section of about 150 mb, actually setting the value of the positron beam interaction length for a given target density value. Using as reference value for the positron beam degradation 1/e (*i.e.* one beam lifetime), one can determine the maximum achievable value for $(\rho^- L)_{max} = 1/\sigma_{(rad.bhabha)} \approx 10^{25} cm^{-2}$. The ratio of muon pair production cross-section to the radiative bhabha cross-section determines the maximum value of the conversion efficiency to muon pairs $\epsilon(\mu^+\mu^-)$, where $\epsilon(\mu^+\mu^-)$ is defined as $n(\mu^+\mu^-) = n^+\epsilon(\mu^+\mu^-)$. One can easily obtain, $n(\mu^+\mu^-)_{max} \approx n^+ 10^{-5}$.

We consider as an example an electron density in the plasma of $10^{20} cm^{-3}$, with 10^{11} positrons in the beam, and a target length of 10 m. Two positron beam energies have been studied to have $\sqrt{s} = 0.212$ GeV and $\sqrt{s} = 0.214$ GeV, with an energy spread of 0.3%. The number of $\mu^+\mu^-$ pairs produced per interaction is 0.25×10^4 and 0.5×10^4 for 212 MeV and 214 MeV, respectively.

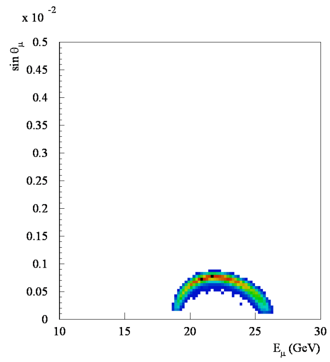

Figure 33-6. *Scattering angle vs muon energy distribution for the $\sqrt{s} = 0.214$ GeV case.*

The present record positron production rate is at the SLAC linac. The SLC collider at SLAC produced high intensity positron bunches at 120 Hz at 46 GeV used to make Z bosons. The positron bunches were accelerated by the S-band linac and had bunch populations of about 4.5×10^{10} positrons, with a length 1 mm (σ) and a low transverse emittance, from the 1.2 GeV damping ring. These positrons were replenished on every pulse using a 4.5×10^{10}-electron bunch hitting a Tungsten-Rhenium target with an s-band high gradient RF capture cavity.

If the primary goal is to produce more positrons per pulse at the SLAC SLC accelerator, then additional electrons per bunch and more bunches per RF pulse could be accelerated If some modest loss in transverse emittances is allowed, an increase of about $\times 1.5$ electrons per bunch is possible. Furthermore, additional electron bunches ($\approx \times 2$) could be accelerated on each RF pulse by careful beam loading management and by using the full RF pulse length. Thus, an overall gain of $\times 3$ is likely.

The production rate of high energy muon pairs from 45 GeV positrons incident on a plasma conversion target can be estimated but should be checked with a experimental test. A low power experimental test of this muon production rate may be possible at the FACET facility at SLAC.

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