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Polarization as a Tool for Studying Particle Properties*

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ABSTRACT

The use of polarized beams in e^+e^- collisions at the Z^0 pole provides a powerful tool for the separation of the charge and spin of the produced fermions. Such a separation is essential for many investigations of particle properties. It is shown that this technique can be used to substantially improve studies of CP violation in neutral B mesons and the charged structure of τ decays.

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1. Introduction

It is well recognized that polarized beams at the Z^0-resonance offer a superior method for studying neutral current coupling parameters. [1] The example of b and τ physics show how useful polarized beams can be for studies beyond neutral current phenomena. Control of the spin of the electron beam offers new experimental possibilities for separating charge or spin of final state fermions. Such a separation is an important starting point for many investigations of the detailed properties of quarks and leptons.

At the Z^0 the cross section for fermion pair production in e^+e^-annihilation is expected to be very large (1 nb for lepton pair production and 4-5 nb for quark pair production). In particular for heavy fermions like the τ lepton or the b quark, the Z^0 offers a production cross section comparable to the one just above threshold. The large production cross section together with polarized beams can make the Z^0-resonance an attractive place to investigate heavy fermion properties.

In the following we first discuss how polarized beams make the forward-backward asymmetry (A_{FB}) at the Z^0 an effective method for separating $B^0\bar{B}^0$ by detector hemispheres. Particle and antiparticle separation is a crucial step to measure CP violation in B decays. [2] In the last part we discuss how the final state τ polarization can be manipulated with polarized beams. [3,4] A sample of polarized $\tau's$ is a basic ingredient for the study of the charged current structure of τ decays.

2. CP Violation in B Decays at the $\mathbf{Z^0}$

CP violation is deeply connected to a difference in the properties of particles and antiparticles. Most experimental investigations of CP violation need an effective method of separating particles and antiparticles.

Attempts to relate the problem of CP violation to the existence of particle generations (Kobayashi–Maskawa (KM) model) [5] make CP violation in connection with heavy quarks very interesting. In B-meson decays sizeable effects are expected.[6] There one tries to measure the following decay asymmetry

$$A_{\mathrm{CP}} \equiv \frac{\Gamma(B^0_{\mathrm{phys}} \to f) - \Gamma(\overline{B}^0_{\mathrm{phys}} \to \overline{f})}{\Gamma(B^0_{\mathrm{phys}} \to f) + \Gamma(\overline{B}^0_{\mathrm{phys}} \to \overline{f})}. \tag{1}$$

The KM model with three generations of quarks predicts large asymmetries for some exclusive non-leptonic modes, and tiny semileptonic decay asymmetries. One expects that interference between mixing and direct decay diagrams, in particular when f is a CP eigenstate, will lead to large asymmetries. Those asymmetries are directly proportional to the CP violating phase in the KM model. One prominent example is the decay of a B^0_d or $\overline{B}^0_d$ into $J/\psi\ K^0_s$. After the recent ARGUS result on B_d mixing [7] these measurements look rather promising. For the measurements of these asymmetries to succeed, it is crucial to distinguish whether the initial beauty meson was a particle (B^0) or an antiparticle ($\overline{B}^0$). We refer to this as the tagging requirement.

Since B-mesons are rarely reconstructed directly simple tagging methods do not exist. The usual technique to experimentally achieve such a separation starts by assuming associated production of quarks. By measuring a property of one of the particles, the identity of the other particle can be tagged. Examples of such tagging techniques are to use the charge of a lepton inside a jet or to try to reconstruct the jet-charge. Normally these tagging methods can only be applied to a small subset of events and one gets a tagging efficiency (ϵ_{tag}) of about 0.1. In a real experimental situation, the particle-antiparticle separation is diluted and one gets a separation asymmetry (A_{sep}), considerably less than unity. We define a 'separation asymmetry' as:

$$A_{\mathrm{sep}} = \frac{N_{\mathrm{correct}} - N_{\mathrm{wrong}}}{N_{\mathrm{correct}} + N_{\mathrm{wrong}}} \tag{2}$$

where the subscripts *correct* and *wrong* refer to correctly and wrongly tagged particles.

With polarized beams at the Z^0, particles and antiparticles are very effectively separated by detector hemispheres (one expects large forward-backward charge asymmetries). This provides a simple and attractive starting point to study CP violation. The following asymmetry tests for CP violation:

$$A_{\mathrm{CP}}^{\mathrm{meas}} = \frac{N(f,\mathrm{forw}) - N(\overline{f},\mathrm{backw})}{N(f,\mathrm{forw}) + N(\overline{f},\mathrm{backw}).} \tag{3}$$

Here, $N(f,\mathrm{forw})$ is the number of decays into the final state in the forward hemisphere and $N(\overline{f},\mathrm{backw})$ is the number of charge-conjugated decays in the backward hemisphere. For example, one can measure the number of neutral B_d meson decays into the CP eigenstate $J/\psi\ K_s^0$ separately in the forward and backward hemispheres. Its simplicity makes it an attractive method to study CP violation in an inclusive way (e.g. one can study gluon or photon asymmetries).

In order to understand the importance of polarized beams we have to discuss the differential cross section for fermion pair production in e^+e^- annihilation. It can be written as

$$\frac{d\sigma}{d\Omega} = \sigma_0 \cdot (1 + \cos^2\theta + 2A_{\mathrm{FB}}^0 \cos\theta), \tag{4}$$

where A_{FB}^0 is the forward-backward asymmetry in the very forward direction and $cos\theta = 1$.

At the Z^0-resonance, the forward-backward asymmetry is generated by the different couplings of the Z^0 to left- and right-handed fermions and is given by

$$A_{\mathrm{FB}}^0 = A_{\mathrm{LR}}^e \cdot A_{\mathrm{LR}}^f \tag{5}$$

where A_{LR}^e is the left-right asymmetry for the coupling of the electron and A_{LR}^f is the left-right asymmetry for the coupling of the final state fermion f to the Z^0.

In Table 1 we show A_{LR}^f for different values of $\sin^2\theta_w$ consistent with the measurement of various neutral current phenomena.[8] Because of the small value

Table 1. Left-right Asymmetries for Various Fermions

$sin^2\theta_w$	0.22	0.23	0.24
$A^{\nu}_{\rm LR}$	1.00	1.00	1.00
$A^{\tau}_{\rm LR}$	0.08	0.16	0.24
$A^{c}_{\rm LR}$	0.64	0.67	0.71
$A^{b}_{\rm LR}$	0.93	0.94	0.94

of $A^e_{\rm LR}$, one expects only small forward-backward asymmetries in fermion pair production at the Z^0.

With polarized beams, the forward-backward asymmetry can be directly manipulated in the experiment. One can introduce a modified left-right asymmetry which takes the initial electron polarization (P_e) into account, and replaces A^e_{LR} by

$$\tilde{A}^e_{\rm LR} = \frac{A^e_{\rm LR} + P_e}{1 + A^e_{\rm LR} \cdot P_e}. \tag{6}$$

Assuming $\sin^2\theta_w = 0.23$, $\tilde{A}^e_{\rm LR}$ will increase to 0.93(0.57) for 90% (45%) polarization. Therefore, with polarized beams we expect a sizeable forward-backward asymmetry for fermion pair production. Table 2 shows the expected $A^0_{\rm FB}$ for the different fermions of one generation assuming $sin^2\theta_w = 0.23$. With polarized electron beams in particular the neutrino and the b-quark will have large asymmetries at the Z^0-resonance.

In the following we compare quantitatively the Forward-Backward tagging (FB tag) with the earlier mentioned Lepton tagging (Lep tag) and estimate how many events are necessary to establish a 3σ asymmmetry (a more detailed discussion can be found in Reference 2):

$$N_{b\bar{b}} = \frac{9.}{A^2_{\rm CP} \cdot A^2_{\rm sep}} \frac{1}{2Br(B^0 \to f)} \frac{1}{\epsilon_f} \frac{1}{\epsilon_{\rm tag}} \frac{1}{\sigma_{B^0}} \tag{7}$$

Table 2. Forward-Backward Asymmetries for Various Fermions

P_e	0.0	0.45	0.90
A^{ν}_{FB}	0.16	0.57	0.93
A^{τ}_{FB}	0.03	0.09	0.15
A^{c}_{FB}	0.10	0.38	0.62
A^{b}_{FB}	0.15	0.54	0.87

where $\mathrm{Br}(B^0 \to f)$ is the branching ratio of the pure B^0 into the CP eigenstate f and ϵ_f is the reconstruction efficiency for that final state f and σ_{B^0} denotes the probability that a beauty quark hadronizes into the neutral B-meson (typically one expects $B_d = 35\%$ and $B_s = 15\%$).

To study the effectiveness of different tagging methods it is convenient to extract the following quality factor out of Equation (7), which contains all the dependence on the tagging technique

$$Q_{\mathrm{sep}} = A^2_{\mathrm{sep}} \cdot \epsilon_{\mathrm{tag}} . \tag{8}$$

This quality factor takes the tagging efficiency and the dilution of the particle-antiparticle separation into account. In Table 3 we compare Q_{sep} for three different methods: Gedanken tagging (i.e., perfect separation of particles and antiparticles), Lepton tagging (as in present B-meson studies) and Forward-Backward tagging (FB tagging) at the Z^0-resonance with polarized beams.

Gedanken tagging simply ignores the experimental tagging requirement and assumes 100% efficiency and 100% separation, hence $Q_{\mathrm{sep}} = 1$. The detailed study in Reference 2 shows that FB tagging (with 90% polarization) requires three times more events, and Lepton tagging requires 33 times more events. Even with 45% polarization FB tagging is four times more effective than the Lepton tagging method.

Table 3. Comparison of Various Methods to Separate Particle and Antiparticle.

Method	A_{sep}	ϵ_{tag}	Q_{sep}	$N_{b\bar{b}}^{\text{equiv}}$
Gedanken Experiment	1.0	1.0	1.0	1.0
Lep - tag	0.50	0.12	0.03	33
FB - tag (no pol.)	0.13	0.63	0.01	100
FB - tag (45% pol.)	0.46	0.63	0.13	8
FB - tag (90% pol.)	0.75	0.63	0.35	3

In the Lep - tag method only those events can be used where a b-quark or $\bar{b}$-quark decays into an electron or muon. In addition, there are severe sources of false charge assignments which will decrease A_{sep}. In particular, in $b\bar{b}$ events the cascade decays ($b \to c \to l$), the $B^0 - \overline{B}^0$ mixing effects and falsely identified, nonprompt leptons result in wrong sign leptons. All together A_{sep} is degraded to about 50%.

In the FB tagging, the separation between particles and antiparticles is not perfect. Here A_{FB} is equivalent to A_{sep} and the actually achieved magnitude of A_{FB} has to be taken into account. Since the forward-backward asymmetry and the cross section is largest at small angles relative to the beam axis, particle detection down to small angles is important. If we integrate the events from $\cos\theta = 0.3$ to $\cos\theta = 0.9$, 63% of the cross section is kept ($\epsilon_{\text{tag}} = 0.63$). With 90% polarization $A_{\text{sep}}=0.75$ within this solid angle; for smaller degrees of beam polarization, it is correspondingly degraded. In Table 3 we show the values for A_{FB} denoted as A_{sep}, which can be achieved for various degrees of incident electron beam polarizations and calculate Q_{sep}. Compared to the Lepton tagging method the FB tagging gains in statistics by about an order of magnitude.

In the following a few promising nonleptonic B_d decays (like e.g. $B_d \to J/\psi\, K_s^0$, $B_d \to D^- D^{*+} + c.c.$, and $B_d \to p\bar{p}$) are used to illustrate the number of events necessary to observe CP violation. Although the asymmetries could be large, branching ratios and detection efficiencies are small. Just from the product of branching ratio and reconstruction efficiency, about 10^5 $N_{b\bar{b}}$ events have to be produced before one can expect to observe one event. Before one can establish a significant asymmetry about one hundred events have to be reconstructed. The tagging requirement comes on top of that. It is therefore no surprise that at least 10^7 $N_{b\bar{b}}$ events are necessary to establish a significant CP violating asymmetry.

In Table 4 the three decay modes mentioned above of the B_d are listed and the three tagging methods, Gedanken-tag, Lepton-tag and FB-tag are compared. The quoted number of $N_{b\bar{b}}$ are necessary to establish a 3 σ asymmetry. A more detailed discussion about the branching ratio, the detection efficiencies and asymmetries used can be found in Reference 2. Since none of the branching ratios are precisely measured, those numbers can be considered as crude estimates; detection efficiencies are somewhat detector dependent.

Table 4. Rate Estimate for an Asymmetry Measurement

Decay	Br $(B \rightarrow f)$	A_{CP}	ϵ_f	$N_{b\bar{b}}$ Gedanken -tag	$N_{b\bar{b}}$ Lep-tag	$N_{b\bar{b}}$ FB-tag (90% pol.)
$B_d \rightarrow J/\psi\ K_s^0$	$5.0 \cdot 10^{-4}$	0.20	0.05	$1.6 \cdot 10^7$	$5.3 \cdot 10^8$	$4.5 \cdot 10^7$
$B_d \rightarrow D^{*+}D^-$	$5.0 \cdot 10^{-3}$	0.20	0.005	$1.3 \cdot 10^7$	$4.2 \cdot 10^8$	$3.6 \cdot 10^7$
$B_d \rightarrow P\overline{P}$	$5.0 \cdot 10^{-5}$	0.3	0.3	$9.5 \cdot 10^6$	$3.1 \cdot 10^8$	$2.7 \cdot 10^7$

With about 50 million $N_{b\bar{b}}$ events and polarized electron beams one can expect to measure CP violation in those nonleptonic decay modes of the B_d. Since the cross section for the reaction $e^+e^- \rightarrow b\bar{b}$ at the Z^0 is about 5 nb, a Z^0-factory with a luminosity of $10^{33} cm^2 sec^{-1}$ would have to run for the canonical 10^7 seconds to produce that many events.

The Z^0 offers an additional important advantage in the investigation of B-mesons. At the Z^0, b jets get a large boost and lifetime information for the B mesons should be easily available. CP violating effects are expected to have a strong time dependence.[9] In particular for the B_s, due to the expected large mixing, time information is crucial in order to establish a CP asymmetry.

3. Charged Current Studies of τ Decays

Many properties of the τ lepton are well measured (e.g. mass, spin and lifetime), but very little is known [10] about the details of the space-time structure of its charged current compared to the μ -decay. [11] A striking example for our limited knowledge is the lack of any direct evidence for parity violation in τ decays.

Most of the detailed studies of the charged current structure need information about the τ polarization as a starting point of the analysis. Experimentally it is unfortunately difficult to achieve such a sample of polarized τ events. One way to prepare a sample of polarized τ events is to use the strong helicity correlation in τ pairproduction. [12] For example, if the helicity of the τ^- is negative the helicity of the τ^+ is positive. The decay $\tau \rightarrow \pi\nu$ under the assumption that the ν is left-handed can be used as a τ spin analyzer. The π momentum in the laboratory frame directly reflects the τ spin. Using this method one can effectively tag the spin of the other τ. In practice this spin correlation tagging has similar deficiencies as the lepton charged tagging for B-meson in the previous chapter. The original τ polarization is only partially reflected in the observed momenta of the decay products and only a certain branching fraction of the τ decay is suitable for a spin tagging (essentially the e, μ, π and ρ). [13] In the reaction $e^+e^- \rightarrow \tau^+\tau^-$ with polarized electron beams, τ particles in the forward or backward hemisphere are highly polarized. This can be understood simply on the basis of helicity conservation. Using the four possible helicity configurations

$$\frac{d\sigma}{d\Omega}(e_L^- e_R^+ \rightarrow \tau_L^- \tau_R^+) = \sigma_0 \cdot (1 + cos\theta)^2 \cdot (1 + \tilde{A}^e_{\mathrm{LR}})(1 + A^\tau_{\mathrm{LR}}), \tag{9}$$

$$\frac{d\sigma}{d\Omega}(e_L^- e_R^+ \rightarrow \tau_R^- \tau_L^+) = \sigma_0 \cdot (1 - cos\theta)^2 \cdot (1 + \tilde{A}^e_{\mathrm{LR}})(1 - A^\tau_{\mathrm{LR}}), \tag{10}$$

$$\frac{d\sigma}{d\Omega}(e^-_R e^+_L \to \tau^-_L \tau^+_R) = \sigma_0 \cdot (1 - cos\theta)^2 \cdot (1 - \tilde{A}^e_{\mathrm{LR}})(1 + A^\tau_{\mathrm{LR}}), \quad \text{and} \tag{11}$$

$$\frac{d\sigma}{d\Omega}(e^-_R e^+_L \to \tau^-_R \tau^+_L) = \sigma_0 \cdot (1 + cos\theta)^2 \cdot (1 - \tilde{A}^e_{\mathrm{LR}})(1 - A^\tau_{\mathrm{LR}}) \tag{12}$$

one can calculate the τ polarization as a function of the scattering angle:

$$P_\tau(cos\theta) = \frac{A^\tau_{\mathrm{LR}} + \tilde{A}^e_{\mathrm{LR}} \frac{2cos\theta}{1+cos^2\theta}}{1 + A^\tau_{\mathrm{LR}} \cdot \tilde{A}^e_{\mathrm{LR}} \frac{2cos\theta}{1+cos^2\theta}} \tag{13}$$

where the left-right asymmetries have the same meaning as in the previous chapter. As we discussed before A^l_{LR} is expected to be small and the main effect arises from the helicity transfer from the initial electron beam (P_e). The main part of the polarization is due only to angular momentum conservation and has nothing to do with parity violation in weak interaction. If we neglect the left-right asymmetry ($A^e_{\mathrm{LR}} = A^\tau_{\mathrm{LR}} = 0$) the τ polarization is given simply by

$$P_\tau(cos\theta) = P_e \cdot \frac{2cos\theta}{1 + cos^2\theta}. \tag{14}$$

It is remarkable that this expression is also relevant for one photon exchange and one expects a strong τ polarization in detector hemispheres even at 10 GeV center-of-mass energy, if the colliding beams are polarized.

Neglecting the lepton left-right asymmetry we compare the two methods (polarized beams and π tag) using a procedure similar to that used in the previous chapter for b-tagging. [4]

For this purpose we introduce a quality factor

$$Q_{pol} = P^2_\tau \cdot \epsilon_{tag}. \tag{15}$$

Table 5. Comparison of Various Methods to Get Polarized τs

Method	P_τ	ϵ_{tag}	Q_{pol}	$N_{\tau\overline{\tau}}^{\text{equiv}}$
Gedanken Experiment	1.0	1.0	1.0	1.0
π - tag	0.50	0.08	0.02	50
Pol - tag (45% pol.)	0.53	0.63	0.18	6
Pol - tag (90% pol.)	0.86	0.63	0.47	2.1

In Table 5 we compare the two methods using this quality factor. Like in the case of b tagging and $B^0\overline{B}^0$ separation polarized electron beams give a significant statistical boost for any investigation which depend on τ polarization.

We use the simple decay $\tau \rightarrow \pi\nu$ to give a rough estimate of the sensitivity one can achieve on right-handed currents, once a sample of polarized $\tau's$ has been prepared. The polarization tagging essentially predicts a certain τ polarization and any deviation of the π momentum spectrum from this prediction indicates a small admixture with no left-handed currents. If f_r is the fraction of right-handed current than we expect the following precision

$$\Delta f_r \simeq \frac{2\%}{\sqrt{Q_{pol}} \cdot \sqrt{\frac{N_{\tau\overline{\tau}}}{10^5}}}. \tag{16}$$

In order to achieve a 2% precision one needs about five million $N_{\tau\overline{\tau}}$ events if one uses momentum correlations in π events. With polarized beams an order of magnitude less events are needed.

Once the systematic error becomes dominant in such an analysis a combination of electron beam polarization and spin correlation tagging can lead to a very large τ polarization with a small error.

The analysis of the leptonic τ decays would profit from a powerful method to get a sample of polarized $\tau's$. Only with polarized $\tau's$ an assumption-free discrimination of V $-$ A versus V $+$ A currents in leptonic decays can be achieved. In particular the parity violating parameter ξ for the leptonic decay spectrum can only be determined if the the initial lepton polarization is known.[14]

The cross section for the reaction $e^+e^- \rightarrow \tau^+\tau^-$ at a center-of-mass energy of 10 GeV and at the Z^0 is about 1 nb, a collider with a luminosity of $10^{33} cm^2 sec^{-1}$ would produce 10 million τ pairs in 10^7 seconds. With polarized beams then very precise studies of the space time structure of the charged current in τ decays would become feasible.

4. Conclusions

The examples of CP violation in B decays and charged current structure in τ decays illustrate the potential of polarized beams in e^+e^-collisions. Most of the examples discussed need one or two orders of magnitude more events than envisaged at presently built machines. Nevertheless the improvement factorizes and those e^+e^-colliders with polarized beams become more sensitive to a surprise.

A high luminosity collider at the Z^0 with polarized beams is an interesting option for the next decade. Such a collider would have many complimentary aspects to a high luminosity collider at 10 GeV in its potential to investigate the properties of quarks and leptons.

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REFERENCES

1. SLCPOL - Collaboration, D. Blockus et. al., SLC Polarization Proposal, April 1986. (see lecture by M. Swartz in these Proceedings).
2. W.B. Atwood, I. Dunietz, P. Grosse-Wiesmann, SLAC-PUB-4544, April 1988
3. Proceedings of the SLC Workshop, SLAC-REPORT-247, March 1982.
4. P. Grosse-Wiesmann, SLAC-PUB-4557, 1988.
5. M. Kobayashi, T. Maskawa, Prog. Theor. Phys. 49, 652 (1973).
6. L.B. Okun, V.I. Zakharov, B.M. Pontecorvo, Lett. Nuovo Cimento 13, 218 (1975); I.I. Bigi, A.I. Sanda, Nucl. Phys. Rev. Lett. 45, 952 (1980).
7. H. Albrecht et al., ARGUS Collaboration, Phys. Lett. 192B, 245 (1987).
8. G. Altarelli, Rome Univ. Report, ROME-529-1986, Oct. 1986, presented at 23rd Int. Conf. on HEP, Berkeley, CA, Jul. 1986, and references therein.
9. I. Dunietz and J. Rosner, Phys. Rev. D34, 1404 (1986).
10. W. Bacino et al., DELCO, Phys. Rev. Lett. 42, 749 (1979), S. Behrends et al., CLEO, Phys. Rev. D32, 2468 (1985), W.T. Ford et al., MAC, Phys. Rev. D36, 1971 (1987).
11. W. Fetscher et al., Phys. Lett. 173B, 102 (1986).
12. Y.S. Tsai, Phys. Rev. D4, 2821 (1971).
13. G. Goggi, LEP Summer Study 1978, Les Houches, CERN 79-01, J.E. Augustin, LEP Summer Study 1978, Les Houches, CERN 79-01, H.J. Behrend et al., CELLO Collaboration, Phys. Lett. 127B, 270 (1983).
14. E.D. Commins and P.H. Bucksbaum, Weak Interactions of Leptons and Quarks, Cambridge University Press, 1983.