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Assessing the Merits of Positron Polarization at a Linear Collider

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Abstract. The possibility of polarized positron beams at a future linear collider has created much interest. At the 2001 Snowmass meeting, a study group (designated E3) included a subgroup whose charge was to closely examine the merits, as quantitatively as possible, of this option. The leading issues are outlined here, and a few physics examples are given. The deciding issues are, however, likely to be technological, as positron polarization would to be a very complex and expensive addition to the accelerator.

I INTRODUCTION

All of the future linear collider (LC) designs include a source of longitudinally polarized electrons, providing high polarization (at least 80%) and for which pulse-to-pulse helicity control will be possible. The option of polarized positron beams is speculative at this time, but polarizations of 40%-60% have been discussed and are considered achievable in principle.

The issues we wish to address are these :

- How compelling are the physics arguments for positron polarization ?
- How encouraging are the technology and cost prospects ?
- Are there any performance tradeoffs (for instance, luminosity) ?

In what follows, only the first question will be briefly addressed - however there will be some discussion of tradeoffs. The technology and cost issues are likely to be the deciding factors, however. The talk to our study group from K. Flöttman addressed some of these questions [**?**].

In one of the two leading polarized positron source designs (the backscattered laser option), pulse-to-pulse polarization control is possible. In the other leading option, which employs helical undulator magnets to produce circularly polarised gamma rays for polarized positron production, schemes for rapid helicity reversal have been discussed which might achieve a high degree left/right systematic error cancellation. We will return to these issues below.

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II POLARIZATION BASICS

The cross section for s-channel vector boson production, and for processes with similar helicity structure, has the form

$$\sigma \sim (1-\mathcal{P}_-)(1+\mathcal{P}_+)g_L^2 + (1+\mathcal{P}_-)(1-\mathcal{P}_+)g_R^2 \tag{1}$$

for positron and electron polarizations $\mathcal{P}_+$ and $\mathcal{P}_-$, and electron left and right neutral current couplings $g_{L/R}$. This cross section is also given by

$$\sigma = \sigma_0[1-\mathcal{P}_-\mathcal{P}_+ - A_{LR}(\mathcal{P}_- - \mathcal{P}_+)], \tag{2}$$

where the unpolarized cross section is σ_0, and A_{LR} is defined in the usual way : $A_{LR} = (g_L^2 - g_R^2)/(g_L^2 + g_R^2)$. When both beams are polarized, an "effective polarization" can be defined such that the cross section definition takes a familiar form

$$\sigma = \sigma_0[1 - A_{LR}\mathcal{P}_{eff}], \tag{3}$$

with

$$\mathcal{P}_{eff} = \frac{\mathcal{P}_- + \mathcal{P}_+}{1+\mathcal{P}_-\mathcal{P}_+}. \tag{4}$$

The effective polarization can be quite large, for example, with electron and positron beams 80% and 60% polarizations respectively, $\mathcal{P}_{eff} = 94.6\%$, and subsequently, the systematic uncertainty of this quantity is reduced.

III EXPERIMENTAL ADVANTAGES OF POSITRON POLARIZATION

It is straightforward to list, and to quantify, the advantages of positron polarization. Subtleties arise when more detailed experimental issues are considered. To begin, here are the fundamental improvements made possible with both beams polarized.

- $\mathcal{P}_{eff} > \mathcal{P}_-$ The larger effective polarization increases observed left-right asymmetries. In addition, the large effective polarization can be used to further enhance signal over background, when compared to electron polarization alone.
- $\delta\mathcal{P}_{eff}/\mathcal{P}_{eff} < \delta\mathcal{P}_-/\mathcal{P}_-$ With both beams polarized and with a precision polarimeter for each of the beams, the measurement error for $\mathcal{P}_{eff}$ is smaller than the measurement error of either polarimeter. This is a simple consequence of error propagation. For example, plausible polarimetry errors of a relative 0.25% [?] lead to an analogous error on $\mathcal{P}_{eff}$ of only 0.1%.

- **All four helicity states are directly accessible.** The LL,RR,LR and RL initial-state helicity configurations are separately controllable. This leads to two separate advantages. Firstly, one would be able to to use the so-called Blondel Scheme [**?**] to eliminate the need for absolute polarimetry, and the associated, and possibly dominant, systematic error. (Two polarimeters, however, would still be required for relative (L versus R) polarization measurement.) Secondly, one would then be able to directly study the four helicity contributions to any physics process.

We now examine each of these issues in a bit more detail.

A $\mathcal{P}_{eff} > \mathcal{P}_-$

The manipulation of polarization for S/N enhancement is most effective when the helicity dependence is maximal, ie. when $A_{LR} = \pm 1$. The holds in W boson pair production, and in single W boson production, due to the dominance of the amplitudes containing a $e_L^- \nu$W vertex.

Comparing the cases where $\mathcal{P}_- = 80\%$, with and without $\mathcal{P}_+$ of 60%, one can use left-handed positron polarization to reduce the background from $0.20\sigma_0$ to $0.08\sigma_0$, as is easily seen from the equations in section II. Thus, a factor of 2.5 improvement in noise reduction is possible. A concurrent increase in signal, for this case a factor of 1.6, also occurs. The manipulation of W boson pair production rates is useful for the control of backgrounds during a W boson threshold scan, where a factor of 2 improvement in the statistical error is possible [**?**] and in any new physics search where W boson production is a troublesome background. For this maximally effective application, one can at most expect an improvement in S/$\sqrt{\text{N}}$ of about a factor of 2.5. It is possible to recover a significant fraction of this performance gain by increased $\mathcal{P}_-$. For example, $\mathcal{P}_- = 92\%$ would provide the same level of background suppression, albeit with less signal enhancement. We will return to the issue of precision W mass measurements below.

B Reduced Polarimetry Uncertainty

Positron polarization would lead to dramatic reductions in polarimetry related systematic error, anywhere from a factor of about 3 to nearly an order of magnitude in principle if the Blondel Scheme is used. However, there is some evidence that once one is in this regime, the limiting systematic error will in fact be due to collision energy uncertainties. This issue is discussed in reference 1. We simply note here that energy calibration is likely to be a very challenging issue at the few MeV levels which apply to future W boson threshold scans.

The so-called giga-Z option, a direct beneficiary of improved polarimetry in the Z-pole A_{LR} measurement, would also encounter problems with energy calibration beyond the precisions reached with about 100 million events, corresponding roughly to 5 MeV uncertainty. The energy calibration issue can be dealt with by running the LC in a reduced-luminosity, reduced-beamstrahlung configuration for the precision electroweak measurements A_{LR} and M_W. In particular for the latter, where the required integrated luminosity will be large, compromises may be necessary. In reference 1, machine configurations are discussed that greatly reduce energy related systematic uncertainty while lowering the luminosity by just over a factor of 4.

Finally, one's ability to interpret the A_{LR} measurement will be limited be the knowledge of $\alpha(M_Z^2)$. A reasonable estimated improvement over our present precision in this parameter is about a factor of 4 [**?**], which also would correspond to the 100 million event statistical error.

C Complete Control of Initial State Helicity

In the Blondel Scheme for reduced polarimetry uncertainty, initial state helicity control is clearly essential. We have already noted in the previous section that beam energy systematics would likely become the dominant issue unless specialized accelerator configurations were used, and we will not discuss this issue further.

The utility of full initial state helicity control for physics studies is a more speculative topic. Within our study group, we have discussed a number of possibilities [**?**]. Two examples taken from supersymmetry physics are the cases of selectron and neutralino pair production.

In selectron pair production, the s-channel (γ and Z boson mediated) amplitude can be turned off relative to the t-channel (neutralino mediated) amplitude, by resticting the e^+e^- initial state helicities to RR or LL. The selectron pair final state configuration of LR or RL is only accessible via the t-channel, while the s-channel produces the LL and RR final states. Using only a polarized electron beam and kinematic information, it is possible to untangle the L and R sleptons in a less direct way, although this becomes increasingly difficult when the L and R sleptons are nearly degenerate in mass, as they are in some models.

For the case of neutralino pair production, several alternative models give different production cross sections for each of the four possible helicity configurations. Unambiguous study of this process would require that both beams be polarized.

For these studies, and for others, one could use electron polarization alone, along with some model assumptions. A question requiring further study is - By these means can one get at the same essential information ? The reader is referred to reference 5 for further discussion.

IV COMMENTS ON MACHINE RELATED ISSUES

There are two topics relevant to precision electroweak physics in the regime where positron polarization has led to greatly reduced polarimetry uncertainty. We have already emphasized the importance of systematic uncertainty due to beam energy measurement in the presence of beamstrahlung effects. More detail is given in reference 1, where it is pointed out that special running conditions, and much effort in instrumentation and energy spectrometery (see the contribution of E.Torrence in these proceedings [?]), will likely be needed. The second issue pertains to the control of the inevitable systematic differences in machine and instrumentation performance which are correlated with beam helicity. At the SLC, the management of small L/R polarization systematics exploited the pulse-to-pulse controllability of the polarized electron source. The helical undulator scheme for positron polarization will not allow this option. It is possible, however, that a fast kicker magnet in combination with two opposite sign spin rotator magnets (these rotators are used to force the bunches into the required transverse orientation for storage in the damping ring) may be used to alleviate this problem. At this time it is not clear if this approach would be practical or sufficient for the highest precision work.

Another issue, applicable to the entire polarized beam program, is to what extent higher electron polarization might compensate for the lack of two polarized beams. If 90% or larger polarization photocathodes become available prior to LC startup, it is certainly simplier to install these than it is to include an expensive and complex polarized positron source.

V CONCLUSIONS

We have critically examined the uses for positron polarization in a future LC. Positron polarization does offer a number of impressive experimental advantages. At the heart of this discussion are the technical issues for polarized positron sources, polarimetry, energy spectrometry, and LC operation. It will be some time before all of these issues are fully understood, in particular, those pertaining to the positron source. It is true, however, that much can be accomplished with a polarized electron source by itself, especially if very high ($> 90\%$) polarizations are achievable.

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