THE PHENOMENOLOGY OF THE LIGHTEST PSEUDO NAMBU GOLDSTONE BOSON AT FUTURE COLLIDERS

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The capability of the linear collider to discover and study the lightest neutral pseudo-Nambu-Goldstone boson ($P^0$) of dynamical symmetry breaking models in the $e^+e^-$ and $\gamma\gamma$ modes is presented. For a number of technicolor $N_{TC} = 4$, the discovery of the $P^0$ at an $e^+e^-$ collider via the reaction $e^+e^- \rightarrow \gamma P^0$ should be possible for an integrated luminosity of $L = 100$ fb$^{-1}$ at $\sqrt{s} = 500$ GeV as long as $m_{P^0}$ is not near $m_Z$. In the $\gamma\gamma$ collider mode the $\gamma\gamma \rightarrow P^0 \rightarrow b\bar{b}$ signal should be very robust and could be measured with high statistical accuracy for a broad range of $m_{P^0}$ if $N_{TC} = 4$.

1 Introduction

Theories of the electroweak interactions based on dynamical symmetry breaking (DSB) avoid the introduction of fundamental scalar fields but generally predict many pseudo-Nambu-Goldstone bosons (PNGB's) due to the breaking of a large initial global symmetry group $G$. Among the PNGB's the colorless neutral states are the lightest ones. Direct observation of a PNGB would not have been possible at any existing accelerator, however light the PNGB's are, unless the number of technicolors, denoted $N_{TC}$, is very large. The phenomenological analysis presented here is extracted from ref. 1, where all the details can be found, and is based on a $SU(8) \times SU(8)$ effective low-energy Lagrangian approach. In the broad class of models considered, the lightest neutral PNGB $P^0$ is of particular interest because it contains only down-type techniquarks (and charged technileptons) and thus will have a mass scale that is most naturally set by the mass of the $b$-quark. The $P^0$ total width is typically in the few MeV range and dominant decay modes are $b\bar{b}$, $\tau^+\tau^-$ and $gg$. Other color-singlet PNGB's will have masses most naturally set by $m_t$, while color non-singlet PNGB's will generally be even heavier.

Detection of the PNGB's at the Tevatron and LHC colliders, has been extensively considered. However, inclusive $gg$ fusion production of a neutral

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*aTalk given at the International Workshop on Linear Colliders, Sitges, Barcelona, Spain, April 28-May 5, 1999.*
PNGB, followed by its decay to $\gamma\gamma$, was not given detailed consideration until recently \(^1\). In this paper it was noticed that for a particular class of models the ratio $\Gamma(P^0 \rightarrow gg)B(P^0 \rightarrow \gamma\gamma)/\Gamma(H \rightarrow gg)B(H \rightarrow \gamma\gamma)$ with $H$ being the SM Higgs and $N_{TC} = 4$ is of the order $10^2$ for $50 \leq m_{P^0}/H$ (GeV) $\leq 150$. Therefore, using the results on the Higgs analysis, we can conclude that, for $N_{TC} = 4$, the $P^0$ can be detected in the $gg \rightarrow P^0 \rightarrow \gamma\gamma$ mode for at least $30 - 50 < m_{P^0} < 150 - 200$ GeV, or perhaps also at Tevatron RunII with $S/\sqrt{B} \geq 3$ for $m_{P^0} \geq 60$ GeV.

2 $e^+e^-$ mode

The best mode for $P^0$ production at an $e^+e^-$ collider (with $\sqrt{s} > m_Z$) is $e^+e^- \rightarrow \gamma P^0$. Because the $P^0Z\gamma$ coupling-squared is much smaller than the $P^0\gamma\gamma$ coupling-squared, the dominant diagram is $e^+e^- \rightarrow \gamma \rightarrow \gamma P^0$. Even when kinematically allowed, rates in the $e^+e^- \rightarrow ZP^0$ channel are substantially smaller, as we shall discuss. We will give results for the moderate value of $N_{TC} = 4$. For $\sqrt{s} = 200$ GeV, we find that, after imposing an angular cut of $20^\circ \leq \theta \leq 160^\circ$ on the outgoing photon (a convenient acceptance cut that also avoids the forward/backward cross section singularities but is more than 91% efficient), the $e^+e^- \rightarrow \gamma P^0$ cross section is below 1 fb for $N_{TC} = 4$. Given that the maximum integrated luminosity anticipated is of order $L \sim 0.5$ fb$^{-1}$, we conclude that LEP2 will not allow detection of the $P^0$ unless $N_{TC}$ is very large.

The cross section for $e^+e^- \rightarrow \gamma P^0$ at $\sqrt{s} = 500$ GeV, after imposing the same angular cut, ranges from 0.9 fb down to 0.5 fb as $m_{P^0}$ goes from zero up to $\sim 200$ GeV. For $L = 50$ fb$^{-1}$, we have at most 45 events with which to discover and study the $P^0$. The $e^+e^- \rightarrow ZP^0$ cross section is even smaller. Without cuts and without considering any specific $Z$ or $P^0$ decay modes, it ranges from 0.014 fb down to 0.008 fb over the same mass range. If TESLA is able to achieve $L = 500$ fb$^{-1}$ per year, $\gamma P^0$ production will have a substantial rate, but the $ZP^0$ production rate will still not be useful. Since the $\gamma P^0$ production rate scales as $N_{TC}^2$, if $N_{TC} = 1$ a $\sqrt{s} = 500$ GeV machine will yield at most 3 (30) events for $L = 50$ fb$^{-1}$ (500 fb$^{-1}$), making $P^0$ detection and study extremely difficult. Thus, we will focus our analysis on the $N_{TC} = 4$ case.

In order to assess the $\gamma P^0$ situation more fully, we must consider backgrounds. The dominant decay modes of the $P^0$ are typically to $b\bar{b}$, $\tau^+\tau^-$ or $gg$. For the $b\bar{b}$ and $gg$ modes, the backgrounds relevant to the $\gamma P^0$ channel are $\gamma b\bar{b}$, $\gamma c\bar{c}$ and $\gamma q\bar{q}$ ($q = u, d, s$) production. The cross sections for these processes obtained after integrating over a 10 GeV bin size in the quark-antiquark mass
are, for $10 \lesssim m_{\tilde{p}_0} \lesssim 80$ GeV and $m_{\tilde{p}_0} \geq 100$ GeV, of the same order of the signal.

Results for $S/\sqrt{B}$, in the various tagged channels, for $N_{TC} = 4$ and assuming $L = 100$ fb$^{-1}$ (and $L = 500$ fb$^{-1}$) at $\sqrt{s} = 500$ GeV, are plotted in Fig. 1. We have assumed a mass window of $\Delta M_X = 10$ GeV in evaluating the backgrounds in the various channels. Also shown in Fig. 1 is the largest $S/\sqrt{B}$ that can be achieved by considering (at each $m_{\tilde{p}_0}$) all possible combinations of the $gg$, $c\bar{c}$, $b\bar{b}$ and $\tau^+\tau^-$ channels. From the figure, we find for $L = 100$ fb$^{-1}$ $S/\sqrt{B} \geq 3$ (our discovery criterion) for $m_{\tilde{p}_0} \leq 75$ GeV and $m_{\tilde{p}_0} \geq 130$ GeV, i.e. outside the $Z$ region. A strong signal, $S/\sqrt{B} \sim 4$, is only possible for $m_{\tilde{p}_0} \sim 20 - 60$ GeV. As the figure shows, the signal in any one channel is often too weak for discovery, and it is only the best channel combination that will reveal a signal. For the TESLA $L = 500$ fb$^{-1}$ luminosity, $S/\sqrt{B}$ should be multiplied by $\sim 2.2$ and discovery prospects will be improved. Tagging and mistagging efficiencies have been included.

After discovery, one can determine branching fractions in various channels and couplings. The only channel with reasonable ($\leq 15\%$) statistical error would be $b\bar{b}$, for $L = 500$ fb$^{-1}$.

![Figure 1: The statistical significances $S/\sqrt{B}$ for a $P^0$ signal in various ‘tagged’ channels as a function of $m_{\tilde{p}_0}$ at a 500 GeV collider for integrated luminosities of 100 fb$^{-1}$ and 500 fb$^{-1}$.](image)
3 γγ mode

By folding the cross section for the \( P^0 \) production at a given energy \( E_{\gamma\gamma} \) of a \( \gamma\gamma \) collider with the differential luminosity, one gets

\[
N(\gamma\gamma \rightarrow P^0 \rightarrow F) = \frac{8\pi\Gamma(P^0 \rightarrow \gamma\gamma)B(P^0 \rightarrow F)}{m_{P^0}^2 E_{e^+e^-}} \tan^{-1} \frac{\Gamma_{\exp}}{\Gamma_{P^0}} \times (1 + \langle \lambda\lambda' \rangle) G(y_0)L_{e^+e^-},
\]

(1)

where \( y_0 = m_{P^0}/E_{e^+e^-} \), \( \lambda \) and \( \lambda' \) are the helicities of the colliding photons, \( \Gamma_{\exp} \) is the mass interval accepted in the final state \( F \) and \( L_{e^+e^-} \) is the integrated luminosity for the colliding electron and positron beams. For initial discovery one chooses initial laser polarizations \( P \) and \( P' \) and \( e^+e^- \) beam helicities \( \lambda e \) and \( \lambda' e \) for a broad spectrum \( 2\lambda e P \sim +1, 2\lambda' e P' \sim +1, PP' \sim +1 \) such that \( G \gg 1 \) and \( \langle \lambda\lambda' \rangle \sim 1 \) (which suppresses \( \gamma\gamma \rightarrow q\bar{q} \) backgrounds) over the large range \( 0.1 \leq y_0 \leq 0.7 \). The \( P^0 \) is always sufficiently narrow that \( \tan^{-1} \rightarrow \pi/2 \).

In this limit, the rate is proportional to \( \Gamma(P^0 \rightarrow \gamma\gamma)B(P^0 \rightarrow \gamma\gamma) \). For the \( P^0 \), \( \Gamma(P^0 \rightarrow \gamma\gamma) \) is large and the total production rate will be substantial.

Since it is well-established \( \gamma \gamma \) that the SM \( h \) can be discovered in this decay mode for \( 40 < m_h < 2m_W \), it is clear that \( P^0 \) discovery in the \( b\bar{b} \) final state will be possible up to at least 200 GeV, down to \( 0.1\sqrt{s} \sim 50 \) GeV (at \( \sqrt{s} \sim 500 \) GeV), below which \( G(y) \) starts to get small. Discovery at lower values of \( m_{P^0} \) would require lowering the \( \sqrt{s} \) of the machine. For the \( b\bar{b} \) channel, the statistical significance \( S/\sqrt{B} \) is plotted in Fig. 4.

Once the \( P^0 \) has been discovered, either in \( \gamma\gamma \) collisions or elsewhere, one can configure the \( \gamma\gamma \) collision set-up so that the luminosity is peaked at \( \sqrt{s}_{\gamma\gamma} \sim m_{P^0} \). A very precise measurement of the \( P^0 \) rate in the \( b\bar{b} \) final state will then be possible if \( N_{TC} = 4 \). For example, rescaling the SM Higgs 'single-tag' results of Table 1 of Ref. 1 (which assumes a peaked luminosity distribution with a total of \( L = 10 \) fb\(^{-1} \)) for the 106 GeV \( \leq m_{jj} \leq 126 \) GeV mass window to the case of the \( P^0 \), we obtain \( S \sim 5640 \) compared to \( B \sim 325 \), after angular, topological tagging and jet cuts. This implies a statistical error for measuring \( \Gamma(P^0 \rightarrow \gamma\gamma)B(P^0 \rightarrow b\bar{b}) \) of \( \lesssim 1.5\% \). Systematic errors will probably dominate. Following the same procedure for \( N_{TC} = 1 \), we find (at this mass) a statistical error for this measurement of \( \lesssim 5\% \). Of course, for lower masses the error will worsen. For \( N_{TC} = 4 \), we estimate an error for the \( b\bar{b} \) rate measurement still below 10\% even at a mass as low as \( m_{P^0} = 20 \) GeV (assuming the \( \sqrt{s} \) of the machine is lowered sufficiently to focus on this mass without sacrificing luminosity). For \( N_{TC} = 1 \), we estimate an error for the \( b\bar{b} \) rate measurement of order \( 15 - 20\% \) for \( m_{P^0} \sim 60 \) GeV.

4
4 Conclusions

We have reviewed the production and study of the lightest pseudo-Nambu Goldstone state $P^0$ of a typical technicolor model at future colliders, focusing mainly on $e^+e^-$. For $N_{TC} = 4$, discovery of the $P^0$ in the $gg \rightarrow P^0 \rightarrow \gamma\gamma$ mode at the LHC will be almost certainly be possible unless its mass is either very small ($\lesssim 30$ GeV?) or very large ($\gtrsim 200$ GeV?), where the question marks are related to uncertainties in LHC backgrounds in the inclusive $\gamma\gamma$ channel.

In contrast, an $e^+e^-$ collider, while able to discover the $P^0$ via $e^+e^- \rightarrow \gamma P^0$, so long as $m_{P^0}$ is not close to $m_Z$ and $N_{TC} \geq 3$, is unlikely (unless the TESLA 500 fb$^{-1}$ per year option is built or $N_{TC}$ is very large) to be able to determine the rates for individual $\gamma F$ final states ($F = b\bar{b}, \tau^+\tau^-$, $gg$ being the dominant $P^0$ decay modes) with sufficient accuracy as to yield more than very rough indications regarding the important parameters of the technicolor model.

The $\gamma\gamma$ option at an $e^+e^-$ collider is actually a more robust means for discovering the $P^0$ than direct operation in the $e^+e^-$ collision mode. For $N_{TC} = 4$, $\gamma\gamma \rightarrow P^0 \rightarrow b\bar{b}$ should yield an easily detectable $P^0$ signal for $0.1 \lesssim \frac{m_{P^0}}{\sqrt{s}} \lesssim 0.7$. Once $m_{P^0}$ is known, the $\gamma\gamma$ collision set-up can be reconfigured to yield a luminosity distribution that is strongly peaked at $\sqrt{s}_{\gamma\gamma} \sim m_{P^0}$ and, for much of the mass range of $m_{P^0} \lesssim 200$ GeV, a measurement of
\( \Gamma(P^0 \to \gamma\gamma)B(P^0 \to b\bar{b}) \) can be made with statistical accuracy in the \( \lesssim 2\% \) range.

A \( \mu^+\mu^- \) collider would be crucial for detecting a light \( P^0 \) (\( m_{P^0} \lesssim 30 \text{ GeV} \)) and would play a very special role with regard to determining key properties of the \( P^0 \). In particular, the \( P^0 \), being, in the class of models we have considered, comprised of \( \bar{D}D \) and \( \bar{E}E \) techniquarks, will naturally have couplings to the down-type quarks and charged leptons of the SM. Thus, \( s\)-channel production (\( \mu^+\mu^- \to P^0 \)) is predicted to have a substantial rate for \( \sqrt{s} \sim m_{P^0} \). Because the \( P^0 \) has a very narrow width, in order to maximize this rate it is important that one operates the \( \mu^+\mu^- \) collider so as to have extremely small beam energy spread, \( R = 0.003\% \). The complete analysis of how the precision \( \mu^+\mu^- \) measurements of various channel rates together with LHC and \( e^+e^- \) measurement can determine (up to a discrete set of ambiguities) the parameters of the effective low-energy Yukawa Lagrangian that determine \( T_3 = -1/2 \) fermion masses and their couplings to the \( P^0 \) can be found in [1].

**Acknowledgments**

I would like to thank R. Casalbuoni, S. De Curtis, A. Deandrea, R. Gatto and J. Gunion for the fruitful and enjoyable collaboration on the topics covered here and R. Rückl for interesting discussions.

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