SUMMARY OF THE EXTENSIONS OF THE STANDARD MODEL
WORKING GROUP

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ABSTRACT

We summarize the results of the extended gauge group working group of the Madison-Argonne Workshop on Present and Future Colliders. Contributions are described on the previously unexamined two photon fusion production of heavy leptons, new studies of $Z'$ couplings to $\overline{\nu}\nu$ and $q\overline{q}$, and previously unexplored vector leptoquark production. More detailed accounts of these studies can be found in individual contributions.

1. Introduction

A universal prediction of extensions of the standard model is the existence of new particles. Depending on the specific model under consideration possible new particles may be extra gauge bosons, new types of fermions, or leptoquarks. The discovery of any of these new particles would dramatically show that the standard model is dead. The race would be on to solve the puzzle of the new standard model. Thus, there is a great deal of interest in constructing methods of measuring the properties of newly found particles. Ultimately, this knowledge is necessary for understanding what the underlying theory might be.

In this context, the contributions to the Extensions of the Standard Model working group consisted of an eclectic mix of the previously unexamined two photon fusion production of heavy leptons, new studies of $Z'$ couplings to $\overline{\nu}\nu$ and $q\overline{q}$, and previously unexplored vector leptoquark production. The analysis of the two photon fusion process found that it is an important mechanism for the production of charged lepton pairs providing the lepton mass, $m_L$, is below about 250 GeV. The $Z'$ studies showed how detailed studies of $Z'$ production and decay can provide additional information on $Z'$ couplings, necessary for the unravelling of the nature of a newly discovered $Z'$ bosons. The leptoquark group performed a first calculation of vector leptoquark production at hadron colliders via $gg$ fusion. They find cross sections which are substantially larger than those obtained earlier for the scalar LQ case which has important implications on limits and properties of vector leptoquarks.

The results of these studies are briefly summarized below. We encourage the interested reader to read the more detailed individual contributions to these proceedings.
2. New Probes of $Z'$ Couplings at the SSC and LHC

Exploring the nature of newly discovered particles is significantly more difficult at hadron supercolliders, such as the SSC and LHC, than at $e^+e^-$ colliders such as LEP, SLC, or NLC. If a new neutral gauge boson, $Z'$, were to be discovered in $pp \to Z' \to l^+l^-$ channel, it would be extremely important to learn as much as possible about the nature of its couplings in order to identify which $Z'$ of the many proposed in the literature (if any!) has been found. During the last few years there has been a great amount of work by many authors on this problem. This work has shown that $Z'$ identification may be possible for relatively light $Z'$s in the 1 TeV mass range although almost all of the individual proposals have suffered from some sort of weakness, usually associated with statistics or backgrounds from SM processes. Clearly, it is of some importance to have as many tools available as possible to deal with this identification problem as they may be applicable to other forms of new, non-SM physics as well as to the $Z'$ situation itself.

There are a rather large number of contenders for a possible $Z'$, a few of which are rather well known and we limit ourselves to those few extended electroweak models(EEM) in the discussion below: (i)the Left-Right Symmetric Model(LRM) which has a single free parameter, $\kappa = g_R/g_L$, the ratio of the $SU(2)_R$ and $SU(2)_L$ coupling constants, the Alternative Left-Right Model(ALRM), a $Z'$ with SM-like couplings(SSM), and the $E_6$- inspired Effective Rank-5 Models(ER5M).

In these proceedings, Hewett and Rizzo have discussed three techniques which may provide additional information on the nature of the $Z'$ coupling to $\nu\bar{\nu}$ and $q\bar{q}$. For each of them the major obstacle to overcome is background from SM processes. In all cases it was assumed that the $Z'$ had already been discovered and had its mass and width well determined via the usual Drell-Yan production mechanism.

The first case examined was $Z' \to jj$ which was shown to be observable in some models in the analysis performed by the ATLAS collaboration provided sufficient jet pair mass resolution is available and the $Z'$ is not too heavy. The idea is straightforward: first one takes the full dijet sample (after smearing with the detector resolution) with pair masses($M_{jj}$) in the range 0.7-1.5 $M_{Z'}$ and applies strong rapidity and $p_t$ cuts, $-1 < \eta < 1$ and $p_t > 0.2 M_{Z'}$. Since most QCD induced events are t-channel dominated, this substantially increases the ratio of signal($S$) to background($B$). Since the width-to-mass ratio of $Z'$s is generally small ($\leq 0.05$), and will in fact be known, clearly almost all of the $Z'$ events will be in the ‘signal’ region 0.9-1.1 $M_{Z'}$. Removing this region from the data sample, the dijet mass distribution remaining events are fit by a 7th order polynomial once an overall factor of $M_{jj}^{-5}$ is removed. Increasing the order of the polynomial was not found to improve the $\chi^2/d.o.f.$ of the fit. Extrapolating this fit into the signal region and subtracting, one is left with a potential excess of $Z'$ events which is then fitted to either a Gaussian or Breit-Wigner distribution. Summing the event excess and scaling by the number of $M_{jj}^{-5}$ is removed. Increasing the order of the polynomial was not found to improve the $\chi^2/d.o.f.$ of the fit. Extrapolating this fit into the signal region and subtracting, one is left with a potential excess of $Z'$ events which is then fitted to either a Gaussian or Breit-Wigner distribution. Summing the event excess and scaling by the number of $Z' \to l^+l^-$ events in the discovery channel reduces systematic errors and provides a handle on the ratio $R = \Gamma(Z' \to jj)/\Gamma(Z' \to l^+l^-)$, which is quite sensitive to the various couplings of the $Z'$.

While this procedure works rather well for a $M_{Z'}=1$ TeV at both the SSC and LHC at design luminosities in a number of different models, the situation was shown to be much more problematic (though not impossible) at higher masses due to a loss
in statistical power.

In a second analysis, Hewett and Rizzo propose a method to get some information on the ratio \( r_{\nu\nu Z} = \frac{\Gamma(Z' \rightarrow Z\nu\bar{\nu})}{\Gamma(Z' \rightarrow l^+l^-)} \), which has been proposed as a probe of \( Z' \) couplings, for \( Z' \) masses in the 1 TeV range. The SM background to this decay arises from the \( pp \rightarrow 2Z \) process with one \( Z \rightarrow \nu\bar{\nu} \) decay. However, Hewett and Rizzo found that this background could be quite precisely determined by measuring the \( p_t \) distribution of the \( Z \) in the corresponding \( pp \rightarrow Zl^+l^- \) process and then rescaling by the ratio of the \( Z \rightarrow \nu\bar{\nu} \) to \( Z \rightarrow l^+l^- \) branching fractions as determined by LEP, after suitably acceptance corrections and rapidity cuts are applied. For a 1 TeV \( Z' \), demanding \( 200 \text{ GeV} < p_t(Z) < 500 \text{ GeV} \) yields for a reasonable \( S/\sqrt{B} \) for several extended models which then allows for a determination of \( r_{\nu\nu Z} \). Unfortunately, this method too fails for larger \( Z' \) masses due to a loss in statistics.

A last possibility is to examine monojet event excesses arising from \( Z'j \) associated production where the \( Z' \) decays to neutrinos. Here one actually needs to consider the four processes \( pp \rightarrow Zj, Z'j \rightarrow l^+l^-j, \nu\bar{\nu}j \) subject to the cuts \( |\eta_j| < 2.5 \) and \( p_t^j > 200 \text{ GeV} \) for a 1 TeV \( Z' \). From the number of SM \( Z \) induced \( l^+l^-j \) events, as determined by a dilepton mass reconstruction, the anticipated number of SM \( Z \) monojet events can be determined via the same rescaled as in the \( r_{\nu\nu Z} \) procedure above. Subtracting this result from the total event sample leaves us with a potential excess induced by the \( Z' \). Scaling the excess by the observed number of \( Z'j \rightarrow l^+l^-j \) events determines the ratio \( R_{\nu} = \frac{\Gamma(Z' \rightarrow \nu\bar{\nu})}{\Gamma(Z' \rightarrow l^+l^-)} \), which is then shown to be quite sensitive to the fermionic couplings of the \( Z' \) and, for most models, is found to lie in the range \( 0 \leq R_{\nu} \leq 3 \). As is the case for the other procedures, this method ceases to work for heavier \( Z' \)'s due to a loss in statistics.

3. Vector Leptoquark Production at the SSC and Tevatron

The existence of leptoquarks (LQ), objects carrying both lepton (L) and baryon (B) numbers with either spin-0 or spin-1, is predicted in many extended electroweak models which attempt to place quarks and leptons on an equal footing.\(^1\) LQ may be searched for either indirectly through their effects on low energy processes or by direct production at various colliders. From LEP we only know that all types of LQ must be more massive than 45 GeV while from HERA we obtain bounds which depend sensitively on the unknown strength of the LQ Yukawa coupling to quarks and leptons. Hadron colliders provide us with another tool with which to find LQ. Since they can be pair produced by \( gg \) or \( q\bar{q} \) fusion, obtainable bounds depend only upon whether the LQ is spin-0 or spin-1 and their branching fraction into \( l^+l^- \) or \( \nu j \). Such searches have already been performed by both the CDF\(^\Box\) and D0 Collaborations\(^\Box\) at the Tevatron for the case of spin-0 LQ pair production, the cross section for which has been known for some time.\(^1\)

For these proceedings, Haber, Hewett, Pakvasa, Pomarol, and Rizzo\(^1\) have calculated the pair production rate for spin-1, vector, LQ at the SSC and Tevatron from the \( gg \) fusion mechanisms. They find cross sections which are substantially larger than those obtained earlier for the scalar LQ case. At the Tevatron, this leads to significantly higher mass limits arising from the existing cross section bounds in comparison to scalar LQ with the same \( l^+l^- \) branching fraction. Unlike the spin-0 case, however, the
pair production of vector LQ (V) involves an additional ambiguity arising from whether or not the V is assumed to be a gauge boson which originates from some extended symmetry group. For the gauge boson case, the various trilinear gVV and quartic ggVV couplings involving vector LQ and gluons are completely determined. If, LQ are not gauge bosons a fair amount of freedom exists in these respective couplings even when we demand CP conservation. Of course, for the non-gauge case there is not much motivation to choose any particular set of these couplings. Blümlein and Rückl consider the case where the vector LQ are minimally coupled, i.e., they have an “anomalous magnetic moment” parameter, \( \kappa = 0 \), whereas in the gauge boson case LQ must have \( \kappa = 1 \). The parton-level gg cross section in the \( \kappa = 0 \) non-gauge case is not expected to obey unitarity but to scale as \( \alpha_s^2 \hat{s}/M_V^4 \) for large \( \hat{s} \). For \( \kappa = 1 \), however, this same cross section behaves as \( \alpha_s^2/\hat{s} \) in the same limit. For the \( q\bar{q} \) process, which is subdominant at both Tevatron and SSC energies, the \( \kappa = 1 \) choice requires the existence of an additional s-channel exchange to maintain unitarity just as both \( \gamma \) and \( Z \) exchanges must be included when obtaining the correct cross section for \( e^+e^- \rightarrow W^+W^- \). This tells us that in a gauge theory of vector LQ, a new spin-1, massive color octet particle must also exist, a scenario realized in both the Abbott-Fahri model as well as \( SU(5) \). As stated above, however, the subdominance of the \( q\bar{q} \) process renders the properties of this new particle academic since its influence on the LQ pair cross section is insignificant and thus production via gg fusion only is considered. Once the value of \( \kappa \) is chosen, the calculation of the parton-level differential cross section is straightforward but algebraically cumbersome.

Single production of LQ’s at hadron colliders is also possible but is more model dependent, making use of the \textit{a priori} unknown \( ql \) or \( \bar{q}l \) Yukawa couplings. For scalar LQ’s, it is well known that this single production scenario can lead to a larger cross section than pair production out to very large LQ masses if the Yukawa coupling is of order electromagnetic strength or greater. A similar result has been found to apply in the case of vector LQ’s. However, as these Yukawa couplings may turn out to be quite small one should not rely solely on this mechanism to provide a source of LQ’s in hadronic collisions.

For details of this analysis, the reader should consult the individual contribution of these authors.

4. Heavy Charged Lepton Pair Production Through Photon Fusion at Hadron Supercolliders

Heavy leptons, both charged and neutral, are a feature of many models which extend the particle content of the Standard Model. The Drell-Yan, gluon fusion, and gauge boson fusion mechanisms for the production of heavy charged leptons in hadron collisions have been investigated in the past. In these proceedings Bhat-tacharya, Kalyniak and Peterson present a preliminary study of the two photon production mechanism, which has been overlooked so far. Both the inelastic process \( pp \rightarrow \gamma\gamma X \rightarrow L^+L^-X \) and the elastic process, \( pp \rightarrow \gamma\gamma pp \rightarrow L^+L^-pp \), were considered in a Weizsäcker-Williams approximation.

The total cross sections for heavy charged lepton pair production in \( pp \) collisions, for the elastic and inelastic two photon fusion processes along with the Drell-Yan and
Fig. 1 The total production cross section (in nanobarns) for a charged lepton pair in $pp$ collisions at the SSC ($\sqrt{s} = 40$ TeV) as a function of its mass $m_L$. The solid curve represents the lepton pair production through two photon fusion in the deep inelastic scattering region of protons, and the dashed curve shows the photon fusion production of $L^+L^-$ for elastic collision of protons. The dotted and dot-dashed curves represent respectively production through gluon fusion and the Drell-Yan mechanisms.

gluon fusion processes are shown in Fig. 1 as a function of the charged lepton mass, for the SSC center of mass energy of 40 $TeV$. These curves were obtained using the HMRS-Set B structure functions. They assumed only three generations of quarks, with the top quark mass set at 150 $GeV$. The gluon fusion cross sections is shown for a Higgs mass of 150 $GeV$.

The Drell-Yan process dominates for low $m_L$. The gluon fusion cross section is relatively flatter with increasing $m_L$ and overtakes the Drell-Yan around $m_L$ of 240 $GeV$ for the SSC and at about $m_L$ of 500 $GeV$ for the LHC. The cross section for the inelastic two photon process is within a factor of 1.4 of that for the dominant Drell-Yan production when $m_L$ is 100 $GeV$. The two photon inelastic production falls to an order of magnitude below the now-dominant gluon fusion process by $m_L$ of about 260 $GeV$.

Hence, the process $pp \rightarrow \gamma\gamma XX \rightarrow L^+L^- XX$ is an important means of production of heavy charged lepton pairs for $m_L$ below 200-250 $GeV$ at SSC energies which cannot be neglected in studies of heavy lepton production at the SSC. In contrast the inelastic two photon process is much less important at LHC energies.

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