Implications of a 300 – 500 GeV/c² Z' boson on pp collider data at √s = 1.8 TeV

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Recent analyses of precision low energy electroweak data indicate that the deviation from the Standard Model predictions of the measurement of atomic parity violation (2.3σ), the effective number of massless neutrinos (2σ), and A_b (2.7σ) could be better described if the existence of an extra Z' neutral gauge boson is assumed. We investigate the implications of a 300 – 500 GeV/c² extra Z' on current pp collider data at √s = 1.8 TeV, including the forward-backward charge asymmetry for very high mass e⁺e⁻ pairs, and the invariant mass spectrum of high mass e⁺e⁻, μ⁺μ⁻, τ⁻τ⁺ and b̄b̄ pairs. For example, a 500 GeV/c² Z' with a total production cross section of ≈ 3 pb and enhanced coupling to the third generation, better describes both the low energy and the Tevatron data.

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Recent analyses [1,2] of precision electroweak data indicate that there are several measurements for which the deviations from the Standard Model predictions are larger than two standard deviations (σ). These include the measurements of atomic parity violation [3] (2.3σ), the effective number of massless neutrinos [4] (2σ), and A_b [4] (2.7σ). These analyses show that the data are better described if an extra Z' neutral gauge boson is assumed. In this analysis, we investigate if there is evidence for a Z' boson in current pp collider data at √s = 1.8 TeV.

We take the parameters and couplings of the Z' to the first generation quarks and leptons from the analysis of the atomic parity violation data by Rosner [1]. Rosner’s analysis indicates that the atomic parity violation data [3] are better described with an E_6 extra Z’ boson. Within this model [3] there is a continuum of Z’ possibilities given by Z’ = Z_0 cos φ + Z_2 sin φ. Rosner’s analysis of the atomic parity violation data yields a best fit for a region of allowed Z’ mass, M_{Z’}, and φ. For example, For φ = 120° the data are best fit with an E_6 Z’ with a mass of about 800 GeV/c². For an E_6 Z’ with M_{Z’} = 500 GeV/c², the atomic parity violation data are best fit with φ = 70° ± 5° and φ = 160° ± 5°, and for a Z’ with a mass of 350 GeV/c², these data are best fit with φ = 60° ± 5° and φ = 173° ± 5°.

Erler and Langacker [3] extend the Z’ analysis to include all precision electroweak data, and include more general classes of Z’ models. In one of the cases, the analysis is extended to allow for the coupling to the third generation to be different from the coupling to the first two generations. With these additional parameters, they are not able to place a constraint on M_{Z’}, but the low energy electroweak data prefer a Z’ with a small (but finite) mixing to the Z, and a large coupling to the third generation, as expected in some models [3]. The larger coupling to b̄b̄ pairs is needed to account for the 2.7σ deviation of A_b [4] from the Standard Model prediction.

Although the mass limits [3] from CDF and DØ [5] for a variety of Z’ models are in the 600 GeV/c² range, the limits are reduced [6] by 100 to 150 GeV/c², if the Z’ width (typically Γ_{Z’} ≈ 0.01 M_{Z’}) is increased to account for the possibility of additional decays modes to exotic fermions (which are predicted in E_6 models), and/or supersymmetric particles. The limits are even lower if one includes the possibility of a more general model with enhanced couplings to the third generation. Therefore, we investigate the present Run I collider data for high mass e⁺e⁻, μ⁺μ⁻, τ⁻τ⁺, and b̄b̄ final states, and look for possible signatures for a Z’ extra gauge boson of the kind that is favored by the low energy data. We constrain the relationship between the couplings to the first two generations and the mass of the Z’ to be the same as that for an E_6 Z’ boson from Rosner’s fits to the low energy measurements.

In hadron-hadron collisions at high energies, massive e⁺e⁻ and μ⁺μ⁻ pairs are produced via the Drell-Yan γ∗/Z process. The presence of both vector and axial-vector couplings in this process gives rise to an asymmetry [8], A_{FB}, in the final-state angle of the lepton in the rest frame of the e⁺e⁻ and μ⁺μ⁻ pair (with respect to the proton direction). Within the Standard Model, for M ≫ M_{Z’}, the large predicted asymmetry (≈ 0.61) is a consequence of the interference between the propagators of the γ∗ and Z. New interactions such as an extra Z’ boson result in deviations from the standard model predictions in both dσ/dM and A_{FB}.

Figures 1(a) and 2(b) compare the measured high mass Drell-Yan dσ/dM (CDF [10] and DØ [8]) and A_{FB} (CDF [10]) to theoretical predictions. The Standard Model dσ/dM curve is a QCD NNLO [8] calculation with MRST99 NLO PDFs [12]. The predictions in Figure 1(a) are normalized by a factor F = 1.11, the ratio of the CDF measured total cross section in the Z region [13] to the NNLO prediction (the overall normalization uncertainties are 3.9% for the experimental data and 5% for the NNLO theory). The Standard Model prediction for A_{FB} has been calculated [8] in QCD-NLO with sin²θ_{eff} = 0.232. The measured dσ/dM and A_{FB} values are in good agreement with the standard model
predictions. In the two highest mass bins (4 events in the 300 – 600 GeV/c² range), \( A_{\text{FB}} \) is about 2.2 standard deviations below the standard model prediction (there are 3 events in the negative hemisphere and one event in the positive hemisphere). An asymmetry in the 300 – 600 GeV/c² range which is smaller than the Standard Model prediction could result from the exchange of a 300 – 500 GeV/c² \( Z' \) gauge boson.

For the \( E_6 \) \( Z' \) models that were fit to the low energy electroweak data, the couplings to the first two generations are well constrained. Contributions to the \( Z' \) cross section from \( t\bar{t} \) and \( b\bar{b} \) annihilation are strongly suppressed due to the small \( t\bar{t} \) and \( b\bar{b} \) parton luminosities, even in the case where the \( Z' t\bar{t} \) and \( Z' b\bar{b} \) couplings are strongly enhanced. For a given \( Z' \) mass and \( \phi \), the total \( Z' \) production cross section (in all channels) in \( pp \) collider data at \( \sqrt{s} = 1.8 \text{ TeV} \) thus is determined by the couplings of the \( E_6 \) \( Z' \) to the first and second generation up and down type quarks. The partial width to electrons is also determined. The integrated cross section for \( e^+e^- \) final states, \( \sigma \times \text{BR}(Z' \to e^+e^-) \), is determined by the \( Z' \to e^+e^- \) branching ratio, and is therefore proportional to \( 1/\Gamma_{Z'} \). In contrast, the prediction for \( A_{\text{FB}} \), which results from the interference between the Standard Model and the \( Z' \) amplitudes, is quite insensitive to the \( Z' \) width. In this study, we compare the Run I collider data to a model with a \( Z' \) width of \( \Gamma_{Z'} = 0.1 \text{ M}_{Z'} \) (which is about a factor of 10 larger than the expected width for an \( E_6 \) \( Z' \) boson for the case of universal couplings to all three generations). This allows for enhanced couplings to the quarks of the third generation, or for additional decay modes to exotic fermions or supersymmetric particles.

**FIG. 1.** (a) \( d\sigma/dM \) distribution of \( e^+e^- \) (CDF and DØ) and \( \mu^+\mu^- \) pairs (CDF). The Standard Model theoretical predictions (dashed line) have been normalized (by a factor of 1.11) to the CDF data in the \( Z \) boson mass region. (b) CDF \( A_{\text{FB}} \) versus mass compared to the standard model expectation (dashed). Also shown are the predicted theoretical curves (1.11) for \( d\sigma/dM \) and \( A_{\text{FB}} \) with an extra \( E_6 \) boson with \( M_{Z'} = 350 \text{ GeV/c}^2 \) and \( \Gamma_{Z'} = 0.1 \text{ M}_{Z'} \), for \( \phi = 60^\circ \) (solid) and \( \phi = 173^\circ \) (dotted).

For the \( E_6 \) \( Z' \) models that were fit to the low energy electroweak data, the couplings to the first two generations are well constrained. Contributions to the \( Z' \) cross section from \( t\bar{t} \) and \( b\bar{b} \) annihilation are strongly suppressed due to the small \( t\bar{t} \) and \( b\bar{b} \) parton luminosities, even in the case where the \( Z' t\bar{t} \) and \( Z' b\bar{b} \) couplings are strongly enhanced. For a given \( Z' \) mass and \( \phi \), the total \( Z' \) production cross section (in all channels) in \( pp \) collider data at \( \sqrt{s} = 1.8 \text{ TeV} \) thus is determined by the couplings of the \( E_6 \) \( Z' \) to the first and second generation up and down type quarks. The partial width to electrons is also determined. The integrated cross section for \( e^+e^- \) final states, \( \sigma \times \text{BR}(Z' \to e^+e^-) \), is determined by the \( Z' \to e^+e^- \) branching ratio, and is therefore proportional to \( 1/\Gamma_{Z'} \). In contrast, the prediction for \( A_{\text{FB}} \), which results from the interference between the Standard Model and the \( Z' \) amplitudes, is quite insensitive to the \( Z' \) width. In this study, we compare the Run I collider data to a model with a \( Z' \) width of \( \Gamma_{Z'} = 0.1 \text{ M}_{Z'} \) (which is about a factor of 10 larger than the expected width for an \( E_6 \) \( Z' \) boson for the case of universal couplings to all three generations). This allows for enhanced couplings to the quarks of the third generation, or for additional decay modes to exotic fermions or supersymmetric particles.
cross section in the di-lepton channel would be larger by a factor proportional to $1/\Gamma_{Z'}$.

For an $E_6$ gauge boson with $M_{Z'} = 350$ GeV/$c^2$, $\Gamma_{Z'} = 0.1 M_{Z'}$, and $\phi = 60^0$ (173$^0$), the theoretical prediction ($\times 1.11$) for the integrated total cross section of $e^+e^-$ pairs in the $300 - 400$ GeV/$c^2$ mass range is $73 (31) \ fb$. The corresponding cross section for the Standard Model prediction ($\times 1.11$) in this range is $54 \ fb$. Both the Standard Model cross section, and the cross section including an additional 350 GeV/$c^2$ $Z'$ are consistent with the observed CDF cross section in this range of $81 \pm 47 \ fb$. Our predicted theoretical curves for $d\sigma/dM$ and $A_{FB}$ with an extra $E_6$ boson, for $M_{Z'} = 350$ GeV/$c^2$ and $\Gamma_{Z'} = 0.1 M_{Z'}$, are shown in Figure 1. The total production cross section ($\times 1.11$) for this $Z'$ for $\phi = 60^0$ (173$^0$) is $17 (11) \ pb$. For $A_{FB}$, $\phi = 60^0$ results in a better agreement of theory and data than $\phi = 173^0$. In the $300 - 600$ GeV/$c^2$ range, the probability that the forward backward asymmetry predicted by the Standard Model agrees with CDF data is 2.4% (see Table 1). For $M_{Z'} = 350$ GeV/$c^2$, $\Gamma_{Z'} = 0.1 M_{Z'}$, and $\phi = 60^0$ (173$^0$), the corresponding probability is 13.4% (7.7%).

Because the couplings of the $E_6$ $Z'$ to the first two generations of quarks and leptons are constrained by the fit to the low energy electroweak data, most of this cross section should appear in the form of decay modes to either exotic fermions (which are predicted in $E_6$ models) and/or supersymmetric particles, or decays to third generation quarks. Since the analysis of Erler and Langacker[13] indicates that a larger coupling to the third generation is needed to account for the 2.7 $\sigma$ deviation from the Standard Model of $A_b$, we look for $Z'$ signatures in the invariant mass spectra of $t\bar{t}$ and $b\bar{b}$ high mass pairs. The CDF 95% CL limit on the $b\bar{b}$ cross section[14] for a 350 GeV/$c^2$ $Z'$ varies from 12 pb for a very narrow $Z'$ to 28 pb for a $Z'$ with $\Gamma_{Z'} = 0.3 M_{Z'}$. Therefore, a production cross section of 11 to 17 pb for a 350 GeV/$c^2$ $Z'$ with $\Gamma_{Z'} = 0.1 M_{Z'}$ (which predominantly decays to $b\bar{b}$ pairs) is consistent with these $b\bar{b}$ limits. Note that $Z' \rightarrow t\bar{t}$ decays are either forbidden or strongly phase space suppressed for $M_{Z'} = 350$ GeV/$c^2$.

The Standard Model $e^+e^-$ Drell-Yan cross section for the $300 - 400$ GeV/$c^2$ mass range and the $Z' \rightarrow e^+e^-$ cross section for $M_{Z'} = 350$ GeV/$c^2$ and $\Gamma_{Z'} = 0.1 M_{Z'}$, with $\phi = 60^0$ and $\phi = 173^0$ are summarized in Table 1. The $Z' \rightarrow e^+e^-$ branching ratio and the total $Z'$ production cross section are also shown in the table.

For an $E_6$ gauge boson with $M_{Z'} = 500$ GeV/$c^2$, $\Gamma_{Z'} = 0.1 M_{Z'}$, and $\phi = 70^0$ (160$^0$), the theoretical prediction ($\times 1.11$) for the integrated total cross section of $e^+e^-$ pairs in the $400 - 600$ GeV/$c^2$ mass range is $17 (7) \ fb$. The corresponding cross section for the Standard Model prediction ($\times 1.11$) in this range is $17 \ fb$. Both the Standard Model cross section, and the cross section including an additional 500 GeV/$c^2$ $Z'$ are consistent with the observed CDF cross section in this range of $28 \pm 28 \ fb$. Our predicted theoretical curves for $d\sigma/dM$ and $A_{FB}$ with an extra $E_6$ boson, for $M_{Z'} = 500$ GeV/$c^2$ and $\Gamma_{Z'} = 0.1 M_{Z'}$, are shown in Figure 2. The total (with decay to all channels) production cross section ($\times 1.11$) for this $Z'$, together with the $Z' \rightarrow e^+e^-$ branching ratio and the Standard Model Drell-Yan cross section in the $400 - 600$ GeV/$c^2$ mass range are listed in Table 1. For $A_{FB}$, the prediction for $\phi = 70^0$ gives better agreement with the data than that for $\phi = 160^0$. For $\phi = 70^0$ (160$^0$), the probability that theory and data agree is 6.3% (3.7%) (see Table 1).

We now look for possible signatures of a $Z'$ with these production cross sections in the $b\bar{b}$ and $t\bar{t}$ channels. In the $b\bar{b}$ channel, the CDF 95% CL cross section limit for a $Z'$ boson with $500$ GeV/$c^2$ varies from $3.1 \ pb$ for a very narrow $Z'$ to $5.5 \ pb$ for a $Z'$ with $\Gamma_{Z'} = 0.3 M_{Z'}$. In the $t\bar{t}$ channel, the CDF 95% CL cross section limit for a $Z'$ boson with $M_{Z'} = 500$ GeV/$c^2$ is $7.5 \ pb$. Therefore, a production cross section of $1.7$ to $3.2 \ pb$ for a $500$ GeV/$c^2$ $Z'$ with $\Gamma_{Z'} = 0.1 M_{Z'}$ (see Table 1), which predominantly decays to $b\bar{b}$ and/or $t\bar{t}$ pairs, is consistent with these limits. It is interesting to note that the published $t\bar{t}$ and $b\bar{b}$ mass distributions show a slight excess of events in the $500$ GeV/$c^2$ region.

FIG. 3. The invariant mass distribution of $t\bar{t}$ pairs at CDF (fit with $m_t = 175$ GeV/$c^2$). The published CDF $Z'$ cross section 95% CL upper limit in the $t\bar{t}$ channel is $7.5 \ pb$ at $M_{Z'} = 500$ GeV/$c^2$. The $1.4 \sigma$ excess at $500$ GeV/$c^2$ in the invariant mass spectrum corresponds to a cross section of $2.3 \pm 1.7 \ pb$.

Figure 3 shows the CDF published[6][17] invariant mass distribution of $t\bar{t}$ pairs (assuming $m_t = 175$ GeV/$c^2$). The $1.4 \sigma$ excess at $500$ GeV/$c^2$ in the invariant mass spectrum corresponds to $\sigma \times BR(t\bar{t}) = 2.3 \pm 1.7 \ pb$. Therefore, the CDF $t\bar{t}$ data support the hypothesis of a $Z'$ boson with a large coupling to the third generation. Although $D\bar{O}$ has not searched for resonances in the $t\bar{t}$ channel, the published $D\bar{O}$ mass spectrum[18] for $t\bar{t}$ events is consistent with an enhancement in the $460 - 500$ GeV/$c^2$ region at a similar level. There is also small $1 \sigma$ excess at $500$ GeV/$c^2$ in the CDF $b\bar{b}$ invariant mass spectrum which corresponds to $\sigma \times BR(b\bar{b}) = 1 \pm 1 \ pb$. Therefore, the CDF $b\bar{b}$ data are
also consistent with the hypothesis of a $Z'$ boson with a total production cross section of 1.7 to 3.2 $pb$ which has a small branching ratio to di-leptons and predominantly decays to top and bottom quarks. Note, that for a $Z'$ that mixes with the $Z$, the fits to low energy electroweak data at the $Z$ peak already constrain [2] the level of the coupling of a $Z'$ to $\tau$ leptons to be similar to the couplings to electrons and muons. Therefore, an enhanced signal in the $\tau^+\tau^-$ channel is not expected for a $Z'$ which mixes with the $Z$.

In summary, we find that either a 350 or a 500 $GeV/c^2$ extra $Z'$ with $\Gamma_{Z'} = 0.1 M_{Z'}$ and enhanced couplings to the quarks in the third generation not only gives a mass spectrum and in the forward-backward asymmetry factor of 20 higher luminosity in Run II, improved measurement of the muon anomalous magnetic moment [20].

The total production cross section of 1.7 to 3.2 $GeV/c^2$ in the invariant mass spectrum of high mass of $t\bar{t}$ events at CDF. A $Z'$ in the $350 - 500$ $GeV/c^2$ mass range is also compatible [19] with the latest measurement of the muon anomalous magnetic moment [20]. With the upgraded CDF and DØdetectors, and the anticipated factor of 20 higher luminosity in Run II, improved searches for $Z'$ bosons could be made in the invariant mass spectrum and in the forward-backward asymmetry for all three di-lepton channels ($ee$, $\mu\mu$ and $\tau\tau$). In addition, the improved silicon vertex detectors in both experiments will increase the sensitivity of such searches in $t\bar{t}$ and $b\bar{b}$ final states.

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TABLE I. The measured CDF (preliminary) and predicted data versus Standard Model Drell-Yan cross section $\sigma_{FB}$ in the $300 - 600$ $GeV/c^2$ range and the probability that models can result in the observed $\sigma_{FB}$ (3 events in the negative hemisphere and 1 event in the positive hemisphere) for the Standard Model and models with an extra $Z'$ boson.

| $M_{Z'}(GeV/c^2)$ | $\phi$ | $A_{FB}$ | Probability |
|------------------|--------|---------|-------------|
| data             | $-0.45 \pm 0.47$ | -       | -           |
| $SM$             | $0.612$ | $0.284$ | $13.4\%$    |
| $350$            | $173^0$ | $0.419$ | $7.7\%$     |
| $500$            | $70^0$  | $0.458$ | $6.3\%$     |
| $500$            | $160^0$ | $0.553$ | $3.7\%$     |

TABLE II. CDF (Preliminary) data versus Standard Model Drell-Yan cross section $\sigma_{tot}(fb)$ for two mass bins: $300 - 400$ and $400 - 600$ $GeV/c^2$. Also shown are total Drell-Yan cross sections when an additional $E_\theta Z'$ boson with a mass $M_{Z'}$ with a total width of $\Gamma_{Z'} = 0.1 M_{Z'}$ is included. The $Z'$ di-lepton branching ratio $BR_{ee}(cc)$ and total production cross section $\sigma_{tot}(pb)$ (with final state decays to any particles) are calculated for the values of $\phi$ obtained from Rosner’s fits to low energy data.

| Bin (GeV/c^2) | $M_{Z'}(GeV/c^2)$ | $\phi$ | $\sigma_{tot}(fb)$ | $BR_{ee}(cc)$ | $\sigma_{tot}(pb)$ |
|---------------|-------------------|--------|---------------------|----------------|---------------------|
| $300 - 400$   | $28 \pm 28$       | -      | -                   | -              | -                   |
| $400 - 600$   | $300 - 400$        | $SM$   | $54$                | $17.1$         | $10.9$              |
| $400 - 600$   | $350$              | $60^0$ | $127$               | $0.43\%$       | $17.1$              |
| $400 - 600$   | $350$              | $173^0$| $85$                | $0.29\%$       | $17.1$              |