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Implications of a 300–500 GeV/c^2 Z' boson on $p\bar{p}$ collider data at $\sqrt{s} = 1.8$ TeV

A. Bodek[1,a], U. Baur[2,b]

[1] Departmet of Physics and Astronomy, University of Rochester, Rochester, NY 14627-0171, USA
[2] Department of Physics, State University of New York at Buffalo, Buffalo, NY, 14260, USA

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Abstract. Recent analyses of precision low energy electroweak data indicate that the deviation from the Standard Model predictions of the measurement of atomic parity violation ($2.3\,\sigma$), the effective number of massless neutrinos ($2\,\sigma$), and A_b ($2.7\,\sigma$) could be better described if the existence of an extra Z' neutral gauge boson is assumed. We investigate the implications of a 300– 00 GeV/c^2 extra Z' on current $p\bar{p}$ collider data at $\sqrt{s} = 1.8$ TeV, including the forward-backward charge asymmetry for very high mass e^+e^- pairs, and the invariant mass specstrum of high mass e^+e^-, $\mu^+\mu^-$, $t\bar{t}$ and $b\bar{b}$ pairs. For example, a 500 GeV/c^2 Z' with a total production cross section of $\approx 3\,pb$ and enhanced coupling to the third generation, better describes both the low energy and the Tevatron data.

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] ($2.3\,\sigma$), the effective number of massless neutrinos [4] ($2\,\sigma$), and A_b [4] ($2.7\,\sigma$). 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 $p\bar{p}$ collider data at $\sqrt{s} = 1.8$ 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 [5] there is a continuum of Z' possibilities given by $Z' = Z_\psi \cos\phi + Z_\chi \sin\phi$. 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 $\phi = 120^0$ the data are best fit with an E_6 Z' with a mass of about 800 GeV/c^2. For an E_6 Z' with $M_{Z'} = 500$ GeV/c^2, the atomic parity violation data are best fit with $\phi = 70^0 \pm 5^0$ and $\phi = 160^0 \pm 5^0$, and for a Z' with a mass of 350 GeV/c^2, these data are best fit with $\phi = 60^0 \pm 5^0$ and $\phi = 173^0 \pm 5^0$.

Erler and Langacker [2] 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 [2,6]. The larger coupling to $b\bar{b}$ pairs is needed to account for the $2.7\,\sigma$ deviation of A_b [4] from the Standard Model prediction.

Although the mass limits [7] from CDF and DØ [8] for a variety of Z' models are in the 600 GeV/c^2 range, the limits are reduced [7] by 100 to 150 GeV/c^2, if the Z' width (typically $\Gamma_{Z'} \approx 0.01\,M_{Z'}$) 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^-, $\mu^+\mu^-$, $t\bar{t}$, and $b\bar{b}$ 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 $\mu^+\mu^-$ 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 [5], A_{FB}, in the final-state angle of the *lepton* in the rest frame of the e^+e^- and $\mu^+\mu^-$ pair (with respect to the *proton* direction). Within the Standard Model, for $M \gg M_Z$, the large predicted asymmetry (≈ 0.61) is a consequence of the interference between the propagators of the γ^* and

[a] e-mail: bodek@pas.rochester.edu
[b] e-mail: baur@physics.buffalo.edu

Z. New interactions such as an extra Z' boson result in deviations from the standard model predictions in both $d\sigma/dM$ and A_{FB}.

Figures 1 and 2 compare the measured high mass Drell-Yan $d\sigma/dM$ (CDF [9,10] and DØ [8]) and A_{FB} (CDF [10]) to theoretical predictions. The Standard Model $d\sigma/dM$ curve is a QCD NNLO [11] calculation with MRST99 NLO PDFs [12]. The predictions in Fig. 1a 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 [14] in QCD-NLO with $\sin^2\theta^{lept}_{eff} = 0.232$. The measured $d\sigma/dM$ 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/c^2 range), A_{FB} is about 2.2 standard deviations below the standard model prediction (there are 3 events in the negative hemipshere and one event in the positive hemisphere). An asymmetry in the 300 – 600 GeV/c^2 range which is smaller than the Standard Model prediction could result from the exchange of a 300 – 500 GeV/c^2 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 ϕ, the total Z' production cross section (in all channels) in $p\bar{p}$ collider data at $\sqrt{s} = 1.8$ 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, $\sigma\times\mathrm{BR}(Z' \to e^+e^-)$, is determined by the $Z' \to e^+e^-$ branching ratio, and is therefore proportional to $1/\Gamma_{Z'}$. In contrast, the prediction for A_{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 $\Gamma_{Z'} = 0.1\,M_{Z'}$ (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. The predictions for $d\sigma/dM$ and A_{FB} for the case of the Drell-Yan process including an extra E_6 Z' boson (for a given M and ϕ) are first calculated in leading order in QCD (with MRSR2 NLO PDFs), ignoring contributions from $t\bar{t}$ and $b\bar{b}$ annihilation. $d\sigma/dM$ is then multiplied by a differential K-factor, $K(M)$, which is determined by comparing the leading order prediction for $d\sigma/dM$ including a 50 TeV/c^2 Z' (i.e. effectively no Z' in the model) to the Standard Model $d\sigma/dM$ prediction from the QCD NNLO [11] calculation (with MRST99 NLO PDFs). In the 300 – 400 and 400 – 600 GeV/c^2 ranges, we obtain a differential K-factor of 1.172 and 1.154, respectively. Since we plan to compare to CDF Drell-Yan data, the predictions in Fig. 1a and 2a 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. Because the data show a clustering of events at mass values of 350 and 500 GeV/c^2, we investigate the signatures for a Z' boson with these two mass values. As mentioned earlier, in all of the calculations we use a Z' width of $\Gamma_{Z'} = 0.1\,M_{Z'}$. If we use a smaller width, the cross section in the di-lepton channel would be larger by a factor proportional to $1/\Gamma_{Z'}$.

Table 1. The measured CDF (preliminary) and predicted average A_{FB} in the 300–600 GeV/c^2 range and the probability that models can result in the observed A_{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)	ϕ	A_{FB}	*Probability*
data	–	-0.45 ± 0.47	–
SM	–	0.612	2.4%
350	60^0	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%

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 (×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 (×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±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 Fig. 1. The total production cross section (×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 probabilty 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 [2] indicates that a larger coupling to the third generation is needed to account for the 2.7 σ deviation from the Standard Model of A_b [4], 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 [15] 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 produc-

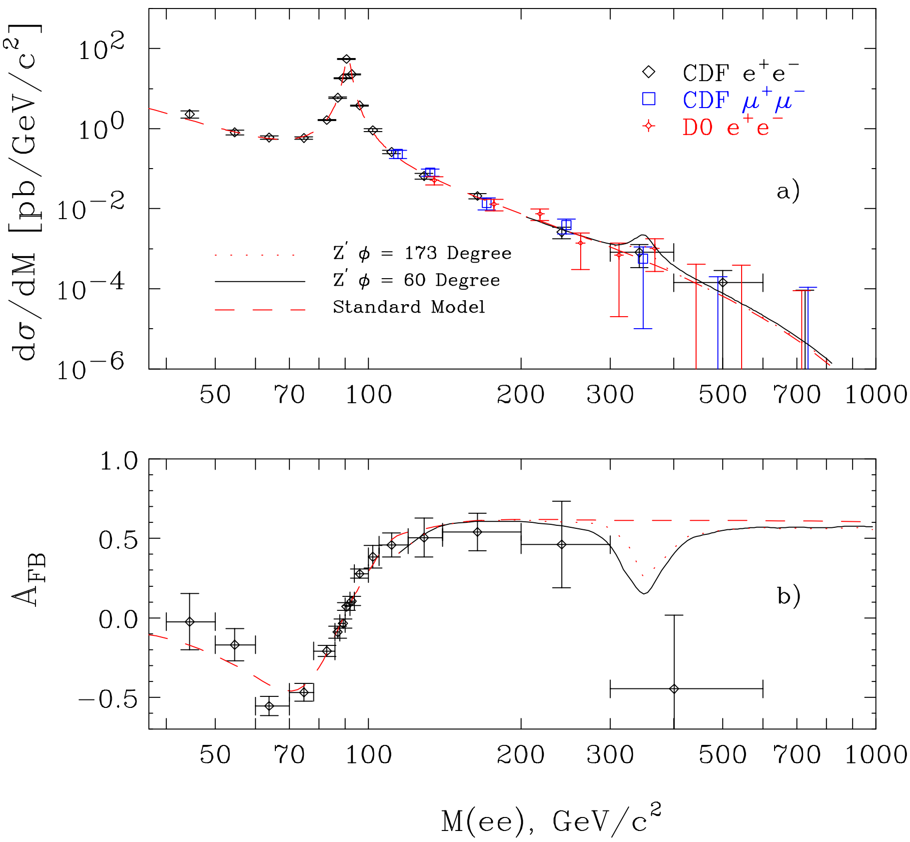

Fig. 1. a $d\sigma/dM$ distribution of e^+e^- (CDF and DØ) and $\mu^+\mu^-$ pairs (CDF). The Standard Model theoretical predictions (dashed line) have been normalized (by a factor of 1.11) to the CDF data in the Z boson mass region. **b** CDF A_{FB} versus mass compared to the standard model expectation (dashed). Also shown are the predicted theoretical curves (×1.11) for $d\sigma/dM$ and A_{FB} with an extra E_6 boson with $M_{Z'} = 350$ GeV/c^2 and $\Gamma_{Z'} = 0.1\,M_{Z'}$, for $\phi = 60^0$ (solid) and $\phi = 173^0$ (dotted)

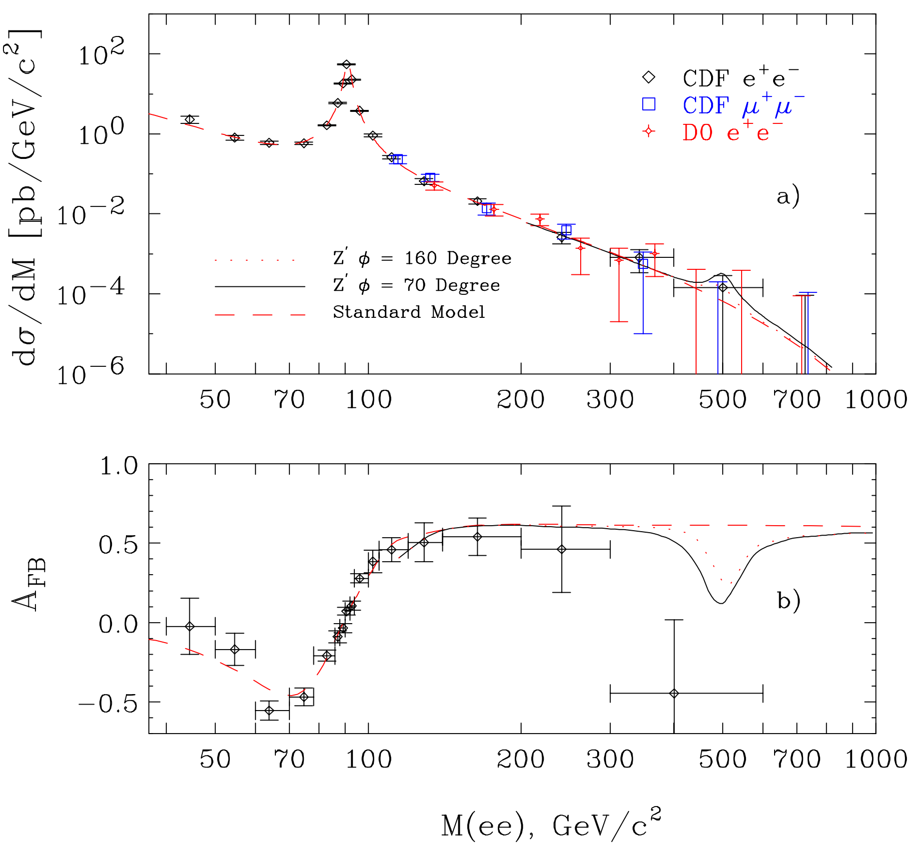

Fig. 2a,b. Same as Fig. 1, but shown here are the predicted theoretical curves for $d\sigma/dM$ (×1.11) and A_{FB} with an extra E_6 boson with $M_{Z'} = 500$ GeV/c^2 and $\Gamma_{Z'} = 0.1\,M_{Z'}$, for $\phi = 70^0$ (solid) and $\phi = 160^0$ (dotted)

Table 2. CDF (Preliminary) data versus Standard Model Drell-Yan cross section $\sigma_{ee}(fb)$ for two mass bins: 300–400 and 400–600 GeV/c^2. Also shown are total Drell-Yan cross sections when an additional E_6 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 $BR(ee)$ and total production cross section σ_{tot} (pb) (with final state decays to any particles) are calculated for the values of ϕ obtained from Rosner's fits to low energy data

Bin (GeV/c^2)	$M_{Z'}$(GeV/c^2)	ϕ	$\sigma_{ee}(fb)$	$BR(ee)$	$\sigma_{tot}(pb)$
300–400	*data*	–	81 ± 47	–	–
300–400	*SM*	–	54	–	–
300–400	350	60^0	127	0.43%	17.1
300–400	350	173^0	85	0.29%	10.9
$400-600$	*data*	–	28 ± 28	–	–
$400-600$	*SM*	–	17	–	–
$400-600$	500	70^0	34	0.53%	3.2
$400-600$	500	160^0	24	0.41%	1.7

tion 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 $Z' \to t\bar{t}$ 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 $Z' \to e^+e^-$ 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 2. The $Z' \to e^+e^-$ 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±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 Fig. 2. The total (with decay to all channels) production cross section ($\times 1.11$) for this Z', together with the $Z' \to e^+e^-$ branching ratio and the Standard Model Drell-Yan cross section in the $400-600$ GeV/c^2 mass range are listed in Table 2. 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 2), 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.

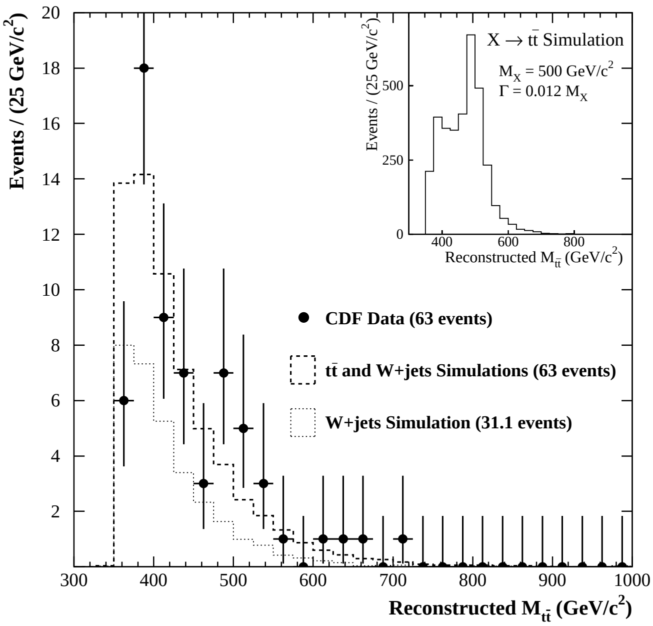

Fig. 3. The invariant mass distribution of $t\bar{t}$ pairs at CDF (fit with $m_t = 175$ GeV/c^2). The published CDF Z' cross section 95% CL upper limit in the $t\bar{t}$ channel is 7.5 pb at $M_{\bar{t}t} =$ 500 GeV/c^2. The $1.4\,\sigma$ excess at 500 GeV/c^2 in the invariant mass spectrum corresponds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

Figure 3 shows the CDF published [16,17] 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 [17] to $\sigma\times\mathrm{BR}(t\bar{t}) = 2.3 \pm 1.7$ pb. Therefore, the CDF $t\bar{t}$ data support the hypothesis of a Z' boson with a large coupling to the third generation. Although DØ has not searched for resonances in the $t\bar{t}$ channel, the published DØ 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 $\sigma\times\mathrm{BR}(b\bar{b}) = 1 \pm 1$ 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 τ 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 better description of the low energy electroweak data, but also provides a somewhat better description of the forward-backward asymmetry for e^+e^- pairs in the 300–600 GeV/c^2

range. A 500 GeV/c^2 extra Z' may also account for the $1.4\,\sigma$ excess at 500 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]. So far, LEPII data have not been compared with the specific Z' model analyzed here. The analyses carried out so far only exclude Z_ψ and Z_χ bosons with $M_{Z_\psi} < 463$ GeV/c^2 and $M_{Z_\chi} < 678$ GeV/c^2 at 95% CL, assuming SM couplings to top and bottom quarks [21]. With the upgraded CDF and DØ detectors, 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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