Baryonic $Z'$ connection of LEP $R_{b,c}$ data with Tevatron $(W, Z, \gamma)\bar{b}b$ events

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Abstract

The mixing of a new $Z'$ boson with the $Z$ significantly improves the fit to the LEP precision electroweak data, provided that the $Z'$ couples mainly to quarks. If $M_{Z'} < 200$ GeV, the $s$-channel $Z_2$ production and $(W, Z, \gamma)Z_2$ pair production cross sections at the Tevatron give an excess above QCD of $\bar{b}b$ and $(W, Z, \gamma)\bar{b}b$ events, respectively, with invariant mass $m(\bar{b}b) \approx M_{Z_2}$, which provide viable signals for detection of the $Z_2$. The interference of the $Z_2$ with $\gamma, Z_1$ in $e^+e^- \rightarrow \bar{b}b(\bar{c}c)$ at LEP 1.5 energies is correlated with $R_b(R_c)$ and may be observable.
The Standard Model (SM) has long provided an excellent representation of particle interactions. Recently, however, possible indications of discrepancies with SM predictions have surfaced in LEP data. The LEP measurements of

$$R_{b(c)} = \frac{\Gamma(Z \rightarrow \bar{b}b(\bar{c}c))}{\Gamma(Z \rightarrow \text{hadrons})}$$

(1)
deviate by $3.7\sigma$ ($-2.4\sigma$) from the SM. These deviations have generated a flurry of phenomenological activity since they may be the first indications of physics beyond the SM. Proposed explanations of the observed phenomena include supersymmetric or other new particles, extra $Z$ bosons, technicolor, and other models. Our interest here is in possible extra $Z$ boson interpretations, which have immediate implications for physics at the Tevatron. We point out that $s$-channel $Z_2$ production and the pair production processes $(W,Z,\gamma)Z_2$ with $Z_2 \rightarrow \bar{b}b$ decays will lead to $\bar{b}b$ and $(W,Z,\gamma)\bar{b}b$ events at the Tevatron, with a $\bar{b}b$ invariant mass peaked at $M_{Z_2}$ in excess of QCD backgrounds if $M_{Z_2} \lesssim 200$ GeV. Here we use $Z_2$ to denote the mass eigenstate of the heavy $Z$ boson after $Z - Z'$ mixing. $Z_2$ interference effects may be observable in $e^+e^- \to \bar{b}b(\bar{c}c)$ at LEP 1.5 energies.

Our work has a distinct vantage point from other recent $Z'$ analyses of the $R_{b,c}$ data that advocate a $Z'$ boson with mass $\approx 1$ TeV to account for an excess above QCD of the inclusive jet cross section at $E_T > 200$ GeV reported by CDF. Although quark distributions are well constrained by deep inelastic scattering data, a smooth rise in the $E_T$ jet cross section compared to QCD expectations can possibly be explained by other means, such as a modification of the gluon structure function at high $x$ or a flattening of $\alpha_s(Q^2)$ at high $Q^2$ due to new particles. Also the CDF high $E_T$ jet anomaly is not present in preliminary D0 data.

A large class of string models with supersymmetry contain additional $U(1)'$ symmetries and additional exotic matter multiplets. In many of these models the $Z'$ and exotic masses are either of $O(M_Z)$ or of order $10^8$ to $10^{14}$ GeV. Consequently a search for $Z'$ bosons in the electroweak mass region $\lesssim 1$ TeV is well motivated. Through the mixing of the $Z'$

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*The values in the Spring 1996 preliminary update are slightly closer to the SM, deviating by $3.5\sigma$ ($-1.8\sigma$).
boson with the $Z$, the predictions of electroweak observables are modified\cite{25,26,27,28}. Thus, it is natural to see if $Z, Z'$ mixing effects can better account for the precision electroweak measurements. In general, this mixing affects both lepton and quark partial widths of the $Z$ as well as the total width. The changes in the widths vary from model to model because of the different chiral couplings. In the usual models based on grand unification with $SO(10)$ or $E_6$ gauge groups (without kinetic mixing\cite{29}), all $Z$ partial widths are modified. However, because the leptonic widths agree well with SM predictions, an overall fit to the electroweak data is then not significantly improved by $Z'$ mixing in these models and the $R_b$ excess is not explained.

If, however, we consider a model in which the $Z'$ couples solely or dominantly to quarks with a universal strength, a substantial improvement results in the description of the precision electroweak data, as detailed below, and found in other recent analyses\cite{7,9,10,11,16}. A reasonable fit to the data is obtained for a range of universal chiral couplings of the $Z'$ boson. A gauge symmetry generated by baryon number, $U(1)_B$, is an interesting possibility\cite{12}, since this avoids potential problems associated with the breaking of global baryon number by quantum gravity effects (e.g., an unacceptable proton decay rate in supersymmetric theories). In this case the $Z'$ has vector couplings. Another possibility is kinetic mixing of the two $U(1)$'s\cite{11,29} to suppress the leptonic couplings. The $U(1)_\eta$ model of $E_6$ is an interesting model in which this may occur\cite{11}. Here the cancellation of contributions to the $Z$-leptonic width is fine tuned and leptonic $Z_2$ decays may still be present at a suppressed level. In the following, we will consider family-universal couplings to baryon and axial-baryon number. As in Refs.\cite{7,10}, we assume that the model can be embedded in an anomaly-free theory. Extension of the results to models (such as $U(1)_\eta$) with different couplings to charge 2/3 and $-1/3$ quarks, or to the family non-universal case, is straightforward.

A $Z'$ coupled to quarks has very interesting implications for physics at the Tevatron collider. If its mass is $\lesssim 200$ GeV, it could be produced in the $s$-channel and in conjunction with the $W$, $Z$ or $\gamma$ and detected via its $Z_2 \rightarrow b\bar{b}$ decay mode (and possibly also through $Z_2 \rightarrow c\bar{c}$). The signatures for $WZ_2$ and $ZZ_2$ production would be similar to Higgs boson production $WH$ and $ZH$, with $H \rightarrow b\bar{b}$ decays, but the $Z_2$ signals could be considerably higher.
Following the notation of Ref. [30], the Lagrangian describing the neutral current gauge interactions of the standard electroweak SU(2) × U(1) and extra U(1)’s is given by

$$\mathcal{L}_{\text{NC}} = eJ_{\text{em}}^\mu A_{\mu} + \sum_{\alpha=1}^{n} g_{\alpha} J_{\alpha}^\mu Z_{0}^{\alpha\mu},$$

(2)

where $Z_{1}^{0}$ is the SM Z boson and $Z_{\alpha}^{0}$ with $\alpha \geq 2$ are the extra Z bosons in the weak-eigenstate basis[31]. In our case, we only consider one extra $Z_{2}^{0}$ mixing with the SM $Z_{1}^{0}$ boson. The coupling constant $g_{1}$ is the SM coupling $g/\cos \theta_{w}$. For grand unified theories (GUT) $g_{2}$ is related to $g_{1}$ by

$$\frac{g_{2}}{g_{1}} = \left(\frac{5}{3} x_{w} \lambda\right)^{1/2} \approx 0.62 \lambda^{1/2},$$

(3)

where $x_{w} = \sin^{2} \theta_{w}$ and $\theta_{w}$ is the weak mixing angle. The factor $\lambda$ depends on the symmetry breaking pattern and the fermion sector of the theory but is usually of order unity.

Since we only consider the mixing of $Z_{1}^{0}$ and $Z_{2}^{0}$ we can rewrite the Lagrangian in Eq. (2) with only the $Z_{1}^{0}$ and $Z_{2}^{0}$ interactions

$$\mathcal{L}_{Z_{1}^{0}Z_{2}^{0}} = g_{1} Z_{1}^{0} \left[ \frac{1}{2} \sum_{i} \bar{\psi}_{i} \gamma^{\mu} \left( g_{v}^{(1)} - g_{a}^{(1)} \gamma^{5} \right) \psi_{i} \right] + g_{2} Z_{2}^{0} \left[ \frac{1}{2} \sum_{i} \bar{\psi}_{i} \gamma^{\mu} \left( g_{v}^{(2)} - g_{a}^{(2)} \gamma^{5} \right) \psi_{i} \right],$$

(4)

where for both quarks and leptons

$$g_{v}^{(1)} = T_{3L}^{i} - 2x_{w} Q_{i}, \quad g_{a}^{(1)} = T_{3L}^{i},$$

(5)

and we consider the case in which $Z_{2}$ couples only to quarks,

$$g_{v}^{(2)} = \epsilon_{V}, \quad g_{a}^{(2)} = \epsilon_{A}, \quad g_{\ell}^{(2)} = g_{a}^{(2)} = 0.$$

(6)

Here $T_{3L}^{i}$ and $Q_{i}$ are, respectively, the third component of the weak isospin and the electric charge of the fermion $i$; $\epsilon_{V}$ and $\epsilon_{A}$ are parameters of the $Z_{2}$ sector. The mixing of the weak eigenstates $Z_{1}^{0}$ and $Z_{2}^{0}$ to form mass eigenstates $Z_{1}$ and $Z_{2}$ can be parametrized by a mixing angle $\theta$

$$\begin{pmatrix} Z_{1} \\ Z_{2} \end{pmatrix} = \begin{pmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{pmatrix} \begin{pmatrix} Z_{1}^{0} \\ Z_{2}^{0} \end{pmatrix}.$$

(7)

The mass of $Z_{1}$ is $M_{Z_{1}} = 91.19$ GeV and $M_{Z_{2}}$ is unknown.
Substituting Eq. (7) into Eq. (4) we obtain the interactions of the mass eigenstates $Z_1$ and $Z_2$ with fermions

$$- \mathcal{L}_{Z_1Z_2} = \sum_i \frac{g_i}{2} \left[ Z_{1\mu} \bar{\psi}_i \gamma^\mu (v_s^i - a_s^i \gamma^5) \psi_i + Z_{2\mu} \bar{\psi}_i \gamma^\mu (v_n^i - a_n^i \gamma^5) \psi_i \right],$$

where

$$v_s^i = g_v^{i(1)} + \frac{g_2}{g_1} \theta g_v^{i(2)}, \quad a_s^i = g_a^{i(1)} + \frac{g_2}{g_1} \theta g_a^{i(2)},$$

$$v_n^i = \frac{g_2}{g_1} g_v^{i(2)} - \theta g_v^{i(1)}, \quad a_n^i = \frac{g_2}{g_1} g_a^{i(2)} - \theta g_a^{i(1)}.$$ (9)

Here we use the valid approximation $\cos \theta \approx 1$ and $\sin \theta \approx \theta$. The Feynman rules for the interactions of $Z_1$ and $Z_2$ with the fermions can be easily obtained from Eq. (8).

### Precision Electroweak Constraints

From studies of $Z'$ mixing effects on the $Z_1$ coupling, the products $\theta \lambda^{1/2} \epsilon_V$ and $\theta \lambda^{1/2} \epsilon_A$ can be determined. Without loss of generality we can take the $\epsilon_V$ and $\epsilon_A$ to be normalized to unity and write

$$\epsilon_V = \sin \gamma, \quad \epsilon_A = \cos \gamma, \quad \kappa = -\theta \left( \frac{5}{3} x_w \lambda \right)^{1/2}.$$ (11)

The partial widths for $Z_1$-decays to quarks are determined by the couplings

$$v_s^b = -\frac{1}{2} + \frac{2}{3} x_w - \kappa \sin \gamma = -0.35 - \kappa \sin \gamma,$$ (12)

$$a_s^b = -\frac{1}{2} - \kappa \cos \gamma = -0.5 - \kappa \cos \gamma,$$ (13)

$$v_s^c = \frac{1}{2} - \frac{4}{3} x_w - \kappa \sin \gamma = 0.19 - \kappa \sin \gamma,$$ (14)

$$a_s^c = \frac{1}{2} - \kappa \cos \gamma = 0.5 - \kappa \cos \gamma,$$ (15)

where the value $x_w = 0.23$ is used in the approximate equalities. The modifications in the SM partial widths are then

$$\delta \Gamma(Z \to b\bar{b}) \simeq \kappa C(M_{Z_1}^2) \Gamma^0(0.69 \sin \gamma + 1.0 \cos \gamma),$$ (16)

$$\delta \Gamma(Z \to c\bar{c}) \simeq -\kappa C(M_{Z_1}^2) \Gamma^0(0.39 \sin \gamma + 1.0 \cos \gamma),$$ (17)
where
\[ \Gamma^0 \equiv \frac{G_F M^3_{Z1}}{2\sqrt{2}\pi} \]  (18)
and
\[ C(Q^2) = 1 + \frac{\alpha_s}{\pi} + 1.409\frac{\alpha^2_s}{\pi^2} - 12.77\frac{\alpha^3_s}{\pi^3}, \]  (19)
with \( \alpha_s = \alpha_s(Q^2) \). Fermion mass corrections, effects related to the shift induced in \( M_Z \) by the mixing [30], and electroweak corrections are not displayed for simplicity but are incorporated in the numerical analysis.

Similar results apply for the other \( T_3 = -1/2 \) and 1/2 flavors, respectively. The total hadronic width
\[ \Gamma(Z \rightarrow \text{hadrons}) = 3\Gamma(Z \rightarrow b\bar{b}) + 2\Gamma(Z \rightarrow c\bar{c}) \]  (20)
is modified by
\[ \delta\Gamma_{\text{had}} = \kappa C\Gamma^0(1.3\sin \gamma + 1.0\cos \gamma). \]  (21)
Thus, a vector baryonic \( Z' (\lambda = \pi/2) \) gives the modifications
\[ \delta\Gamma(Z \rightarrow b\bar{b}) \simeq 0.69\kappa C\Gamma^0, \quad \delta\Gamma(Z \rightarrow c\bar{c}) \simeq -0.39\kappa C\Gamma^0, \quad \delta\Gamma_{\text{had}} \simeq 1.3\kappa C\Gamma^0. \]  (22)
The \( Z \rightarrow b\bar{b} \) partial width is increased (for \( \kappa > 0 \)) and the \( Z \rightarrow c\bar{c} \) partial width is decreased, which are the directions of the deviations from SM predictions indicated by the LEP data. The increase in the total hadronic width can be compensated by a smaller value of \( \alpha_s(M^2_Z) \) in \( C(M^2_{Z1}) \) than that obtained in the SM fits; then both \( \Gamma_{\text{had}} \) and \( \Gamma_{\text{tot}} \) measurements are well described by the \( Z' \) mixing model.

An axial baryonic \( Z' (\gamma = 0) \) gives the changes
\[ \delta\Gamma(Z \rightarrow b\bar{b}) \simeq 1.0\kappa C\Gamma^0, \quad \delta\Gamma(Z \rightarrow c\bar{c}) \simeq -1.0\kappa C\Gamma^0, \quad \delta\Gamma_{\text{had}} \simeq 1.0\kappa C\Gamma^0. \]  (23)
Here the effects in the \( b\bar{b} \) and \( c\bar{c} \) channels are again in the desired direction (for \( \kappa > 0 \)), but larger, and the change in \( \delta\Gamma_{\text{had}} \) is somewhat less. A range of \( \gamma \) values can produce fits that are significantly better than the SM; we focus on \( \gamma = 0 \) and \( \pi/2 \) henceforth as representative cases. Even better fits could be obtained by adjusting \( \gamma \). We will also briefly consider the fine-tuned case \( \cot \gamma = -1.3 \), for which the direct contribution to \( \delta\Gamma_{\text{had}} \) vanishes.
We have made fits to the full set of electroweak measurements similar to analyses of the SM [3]. In particular, we include the (important) constraints from deep inelastic neutrino scattering and atomic parity violation, which were not included in the analyses of Refs. [9,10,11]. The best fit value of $\alpha_s(M_Z^2)$ comes out somewhat low for the pure axial and pure vector cases, so we made subsequent fits with $\alpha_s(M_Z^2)$ fixed at 0.11, 0.115, and 0.12. The chi-square for the axial model is moderately increased by fixing $\alpha_s$ at the higher values, while for the vector model the quality of the fit decreases significantly. The values† for $\alpha_s$, $m_t$, $\theta \lambda^{1/2}$ and $M_2/M_1$ are listed in Tables 1 and 2. Table 3 contains the results of the model with $\cot \gamma = -1.3$. Excellent fits are obtained with $\alpha_s$ close to the SM fit value $\alpha_s = 0.123$. For comparison with the $\chi^2$ values in these fits, the $\chi^2$ value found in the SM fit is $\chi^2 = 192$ for 208 degrees of freedom. Table 4 compares the fit to the interesting observables $R_b$, $R_c$, $R_\ell$, $\Gamma_{\text{had}}$, $\Gamma_{\text{tot}}$ and $A_{\text{FB}}(b\bar{b})$, where the latter quantity is the $b\bar{b}$ asymmetry; the “pull” of each of these observables in the fit is given.

Table 1: Parameters determined by electroweak data analysis for $\gamma = 0$ ($Z'$ with pure axial vector coupling). The $\chi^2$ values are for 206 (207) degrees of freedom for $\alpha_s$ free (fixed). The upper bounds on $M_2/M_1$ are one sigma mass limits.

| $\sin^2 \theta_w$ | $\alpha_s$ | $m_t$    | $\theta \lambda^{1/2}$ | $M_2/M_1$ | $\chi^2$ |
|------------------|-----------|----------|------------------------|-----------|---------|
| 0.2313(2)        | 0.095(8)  | 183$^{+7}_{-11}$ | $-0.025(7)$ | $<1.9$ | 176 |
| 0.2314(2)        | 0.11 fixed | 181$^{+7}_{-10}$ | $-0.014(3)$ | $<2.9$ | 179 |
| 0.2315(2)        | 0.115 fixed | 180$^{+7}_{-9}$ | $-0.011(3)$ | $<3.9$ | 182 |
| 0.2315(2)        | 0.12 fixed  | 179$^{+7}_{-9}$ | $-0.007(3)$ | $<6.3$ | 185 |

In the SM fit the Higgs mass is constrained to the range

$$60 < m_H < 100$$

with the best fit at the lower end of the allowed range. This is driven mainly by $R_b$ and the SLD polarization asymmetry [3]. In the mixing models the preference for any particular

† The shifts in the $Z_1$ couplings depend only on the combination $\theta \lambda^{1/2}$. The shift in $M_{Z_1}$ and the effects of $Z_2$ exchange have different dependences on $\lambda$ and $\theta$. However, the global fit results are insensitive to $\lambda$ in the range 0.25–4 except for the scaling of $\theta$ as $\lambda^{-1/2}$. The fit results are given for $\lambda = 1$. 

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Table 2: Parameters determined by electroweak data analysis for $\gamma = \pi/2$ ($Z'$ with pure vector couplings).

| $\sin^2 \theta_w$ | $\alpha_s$ | $m_t$ | $\theta \lambda^{1/2}$ | $M_2/M_1$ | $\chi^2$ |
|------------------|---------|-----|------------------|---------|--------|
| 0.2313(2)        | 0.068(17) | 181(7) | -0.037(11) | <1.02  | 179    |
| 0.2315(2)        | 0.11 fixed | 179(7) | -0.010(2) | <1.1   | 186    |
| 0.2315(2)        | 0.115 fixed | 179(7) | -0.007(2) | <1.15  | 187    |
| 0.2315(2)        | 0.12 fixed | 179(7) | -0.004(2) | <1.4   | 189    |

The Higgs mass value is weakened significantly, especially for the cases which come close to the experimental $R_\theta$. Our precision electroweak analysis does not include the case of an approximate $Z_2$, $Z$ mass degeneracy [32], since the LEP/SLD extractions of the $Z$-parameters assume a single resonance description. Values of $M_{Z_2} < M_{Z_1}$ area also possible, but we have not analyzed this case in detail.

Table 3: Parameters determined for the model with no direct contribution to $\delta \Gamma_{\text{had}}$ (cot $\gamma = -1.3$). The standard model fit parameters are also shown. The $\chi^2$ are for 206 (208) degrees of freedom.

| $\sin^2 \theta_w$ | $\alpha_s$ | $m_t$ | $\theta \lambda^{1/2}$ | $M_2/M_1$ | $\chi^2$ |
|------------------|---------|-----|------------------|---------|--------|
| $\delta \Gamma_{\text{had}} = 0$ | 0.2312(2) | 0.121(4) | 185(7) | -0.043(11) | <1.2 | 177 |
| SM               | 0.2315(2) | 0.123(4) | 180(7) | —    | —    | 192 |

### $Z_2$ Decays

The decay width of $Z_2(Z_1) \to f \bar{f}$ is given by

$$\Gamma(Z_2(1) \to f \bar{f}) = \frac{G_F M_{Z_2}^2}{6\pi \sqrt{2}} N_c C(M_{Z_2(1)}^2) M_{Z_2(1)} \sqrt{1 - 4x} \left[ v_{n(s)}^2 (1 + 2x) + a_{n(s)}^2 (1 - 4x) \right], \quad (25)$$

where $x = m_f^2 / M_{Z_2(1)}^2$, $N_c = 3$ or 1 if $f$ is a quark or a lepton, respectively, $G_F$ is the Fermi coupling constant, and $M_{Z_2}^0$ is the SM $Z$ mass. We calculated $\alpha_s(M_{Z_2})$ from the two-loop expression with $\Lambda_{\text{QCD}} = 200$ MeV and 5 flavors for $M_{Z_2} < 2m_t$ and 6 flavors above $2m_t$. 

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Table 4: Comparison of fits to the observables \(R_b, R_c, R_\ell, \Gamma_{\text{had}}, \Gamma_{\text{tot}}\) and \(A_{\text{FB}}(\bar{b}b)\). (\(\Gamma_{\text{had}}\) is actually a quantity derived from the standard fit variables[1,2].) For the vector and axial cases, the results are for \(\alpha_s = 0\). Widths are in GeV. For each fit the “pull”, i.e., (fit value − expt. value)/error, is shown in square brackets.

| Baryonic \(Z'\) Model | Expt. (LEP+SLD) | SM | \(\gamma = 0\) (axial) | \(\gamma = \pi/2\) (vector) | \(\cot \gamma = -1.3\) (\(\delta \Gamma_{\text{had}} = 0\)) |
|------------------------|-----------------|------------------|-------------------|-----------------|---------------------|
| \(R_b\)               | 0.2219(17)      | 0.2155 [-3.8]   | 0.2194 [-1.5]     | 0.2170 [-2.9]   | 0.2210 [-0.5]       |
| \(R_c\)               | 0.1540(74)      | 0.172 [2.4]     | 0.166 [1.6]       | 0.170 [2.2]     | 0.164 [1.4]         |
| \(R_\ell\)            | 20.788(32)      | 20.77 [-0.6]    | 20.79 [0.1]      | 20.78 [-0.3]    | 20.78 [-0.3]        |
| \(\Gamma_{\text{had}}\) | 1.7448(30)      | 1.746 [0.4]     | 1.747 [0.7]      | 1.747 [0.7]     | 1.744 [-0.3]        |
| \(\Gamma_{\text{tot}}\) | 2.4963(32)      | 2.500 [1.2]     | 2.501 [1.5]      | 2.500 [1.2]     | 2.497 [0.2]         |
| \(A_{\text{FB}}(\bar{b}b)\) | 0.0997(31)      | 0.102 [0.7]     | 0.102 [0.7]      | 0.102 [0.7]     | 0.100 [0.1]         |

The \(Z_2\) width is proportional to \(\lambda\), which sets the strength of the \(Z_2\) coupling; see Eq. (3). For \(\lambda = 1\) the total \(Z_2\) width is

\[
\Gamma_{Z_2}/M_{Z_2} = 0.022 \quad \text{for } M_{Z_2} < 2m_t, \quad \Gamma_{Z_2}/M_{Z_2} = 0.026 \quad \text{for } M_{Z_2} > 2m_t.
\]

The widths would be increased somewhat if there are open channels for decay into superpartners or exotic particles.

**\(Z_2\) Production in the s-channel**

The \(Z_2\) state can be directly produced at a hadron collider via the \(q\bar{q} \rightarrow Z_2\) subprocesses, for which the cross section in the narrow \(Z_2\) width approximation is[33]

\[
\hat{\sigma}(q\bar{q} \rightarrow Z_2) = K \frac{2\pi G_F M_{Z_2}^2}{\sqrt{2}} \left[ (v_n^q)^2 + (a_n^q)^2 \right] \delta\left(\hat{s} - M_{Z_2}^2\right). 
\]

The \(K\)-factor represents the enhancement from higher order QCD processes, estimated to be[33] \(K = 1 + \frac{\alpha_s(M_{Z_2}^2)}{2\pi^2} \frac{4}{3} \left(1 + \frac{4}{3} \pi^2\right) \simeq 1.3\). In the approximation that the terms proportional to \(\theta\) in the couplings \(v_n^q, a_n^q\) are neglected,

\[
(v_n^q)^2 + (a_n^q)^2 = (0.62)^2 \lambda
\]

(28)
and the cross section is independent of the parameter $\gamma$.

The jet-jet invariant mass resolution smearing of hadron collider detectors is typically $\Delta m(jj)/m(jj) = 0.1$, which includes the effects of QCD radiation and detector smearing. Since this mass resolution well exceeds the $Z_2$ width when the $Z_2$ is $\mathcal{O}(M_Z)$, we include a Gaussian smearing of $m(jj)$ with this rms resolution in calculating $m(jj)$ distributions associated with $Z_2$ decays.

In calculating the QCD background to $s$-channel $Z_2$ production we include interference effects and calculate the $q\bar{q} \rightarrow q\bar{q}$ process at the amplitude level, including $Z_2$, $Z$ and $\gamma$ exchanges along with the QCD gluon exchange amplitudes. The non-interfering backgrounds from the $W$-exchange processes $q\bar{q} \rightarrow q\bar{q}$ and $q\bar{q} \rightarrow q'\bar{q}$ and the backgrounds from $gg$, $gq$, and $g\bar{q}$ initiated processes are added to get the full jet-jet cross section. In our calculations we use the CTEQ3L parton distributions of Ref. [34].

The UA2 Collaboration[35] has detected the $W + Z$ signal in the dijet mass region $48 < m(jj) < 138$ GeV and has placed upper bounds on $\sigma B(Z_2 \rightarrow jj)$ over the range $80 < m(jj) < 320$ GeV. Figure 1 compares our $Z_2$ model predictions for $\lambda = 0.2$, 0.6, and 1 with the UA2 upper bounds. We see that a $\lambda$ upper bound of order 0.7 to 1 is indicated for $100 < M_{Z_2} < 180$ GeV. However, because of the uncertainty in the $K$-factor in the theoretical cross section calculation and the difficulty in obtaining an experimental bound by subtraction of a smooth background, we subsequently consider $\lambda = 1$ at any $M_{Z_2}$ for illustration.

Inclusive $Z_2$ production with $Z_2 \rightarrow b\bar{b}$ decays may be detectable at the Tevatron as an excess of events in the $b\bar{b}$ invariant mass distribution at $m(b\bar{b}) \approx M_{Z_2}$ and in the inclusive transverse momentum distribution of the $b$, which has a Jacobian peak at $p_T(b) \approx \frac{1}{2} M_{Z_2}$. These distributions are illustrated for leading order QCD in Fig. 2. Vertex and semileptonic tagging of the $b$'s can be used to reject the backgrounds from other quarks and gluons. The backgrounds due to $gg \rightarrow b\bar{b}$ production are nonetheless very large, so identification of the signal contribution here is difficult.

The $Z_2$ can be produced in $e^+e^-$ collisions via any direct $e^+e^-$ coupling and its $e^+e^-$ coupling induced by mixing. Here we consider the $e^+e^-$ coupling that results solely from mixing. Figure 3 illustrates the effects of a $M_{Z_2} = 105$ GeV resonance on the $e^+e^- \rightarrow b\bar{b}$ and
$c\bar{c}$ cross sections and on the $e^+e^-\rightarrow \bar{b}b$ forward-backward asymmetry $A_{FB}$. An interference of $Z_2$, $Z_1$ and $\gamma$ contributions gives the wave-like structure, with the interference vanishing close to $\sqrt{s} = M_{Z_2}$. The signs of the interference contributions are opposite in $\bar{b}b$ and $c\bar{c}$ (and are related at $\sqrt{s} < M_{Z_2}$ to the signs of the deviations of $R_b$ and $R_c$ from the SM). Consequently, flavor identification is necessary to observe the effect. To quantify the effect, we take the difference of cross-sections at ±1 GeV on either side of the interference zero. In the $M_{Z_2} = 105$ GeV illustration the values of $\Delta \sigma = \sigma(\sqrt{s} = 104 \text{ GeV}) - \sigma(\sqrt{s} = 106 \text{ GeV})$ are

\begin{align*}
\Delta \sigma_{bb}^{SM+Z_2(axial)} &= 39 \text{ pb}; \\
\Delta \sigma_{bb}^{SM+Z_2(vector)} &= 34 \text{ pb}; \\
\Delta \sigma_{cc}^{SM+Z_2(axial)} &= 0.72 \text{ pb}; \\
\Delta \sigma_{cc}^{SM+Z_2(vector)} &= 11 \text{ pb}; \\
\Delta \sigma_{cc}^{SM} &= 18 \text{ pb}.
\end{align*}

A fine energy scan at LEP 1.5 in the region of $\sqrt{s} = M_{Z_2}$ could measure these $Z_2$ resonance effects.

**Vector Boson Pair Production**

In the SM, $W^+W^-$ and $WZ$ pair production can provide stringent tests of the gauge theory since there are large cancellations between a $s$-channel gauge boson amplitude and a $t$-channel fermion exchange amplitude. For example, consider $p\bar{p} \rightarrow WZ + \text{anything}$ production at $\sqrt{s} = 1.8$ TeV. The components of the cross section are

\begin{align*}
\sigma(W^*) &= 16 \text{ pb}, \\
\sigma(f) &= 20 \text{ pb}, \\
\sigma(W^*, f) &= -34 \text{ pb}, \\
\sigma_{\text{total}} &= 2 \text{ pb},
\end{align*}

where $W^*$ denotes the $s$-channel resonance, $f$ the fermion exchange contribution, and $(W^*, f)$ the interference contribution. This cancellation is mandated by the asymptotic $s$-dependence of the cross section\[33\]. In the case of $WZ_2$ or $ZZ_2$ pair production the $s$-channel boson contributions are highly suppressed by the mixing angle $\theta$. Consequently, we expect much larger pair production cross sections than in the SM when $M_{Z_2}$ is of order $M_Z$. Because the $Z'$ couplings to quarks are universal, there is no reason for a cancellation of $s$- and $t$-channel contributions\[30\].

The cross sections at the Tevatron energy $\sqrt{s} = 1.8$ TeV are shown for $\lambda = 1$ in Fig. 4. We have included a $K$-factor of $K = 1.3$ to approximate next-to-leading order QCD contributions\[37\]. The cross sections for $WZ_2$, $Z_1Z_2$, and $\gamma Z_2$ scale linearly with $\lambda$. 

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For comparison the corresponding SM cross sections for $WZ_1$, $\gamma Z_1$ and $Z_1 Z_1$ are indicated by squares on the figure. We have imposed the acceptance $p_T(\gamma) > 15$ GeV and $|\eta(\gamma)| < 1$ on the final state photon.

The prospects for detecting the $Z_2$ would be best in the $Z_2 \rightarrow b\bar{b}$ final state, with $b$-tagging by vertex detector or semileptonic decays to reject backgrounds from light quarks and gluons in the $(\gamma, W, Z) jj$ final state. The $b\bar{b}$ branching fraction of $Z_2$ is

$$B(Z_2 \rightarrow b\bar{b}) = 0.2.$$  (31)

The signature of $WZ_2$ with $Z_2 \rightarrow b\bar{b}$ are the same as those for Higgs searches in $WH$ and $ZH$ final states with $H \rightarrow b\bar{b}$ decays. Figure 3 compares the $(W, Z, \gamma) b\bar{b}$ cross sections for $\lambda = 1$ with $(W, Z) H \rightarrow b\bar{b}$, where $B(H \rightarrow b\bar{b}) \approx 1$ for the mass range shown. We have included a $K$-factor of $K = 1.25$ to approximate the next-to-leading order QCD contributions\cite{35} to $WH$ and $ZH$ cross sections here. We see that for $M_{Z_2} \approx 105$ GeV the $W + (Z_2 \rightarrow b\bar{b})$ cross section with $\lambda = 1$ is a factor 3 times the $W + (H \rightarrow b\bar{b})$ cross section. Other experimentally interesting channels include $Z_1 + (Z_2 \rightarrow b\bar{b})$ and $\gamma + (Z_2 \rightarrow b\bar{b})$, whose cross sections are also given in Fig. 3. The $Z_1 Z_2$ and $Z_2 Z_2$ cross sections will give $b\bar{b}b\bar{b}$, $b\bar{b}c\bar{c}$, $c\bar{c}c\bar{c}$ events above the SM QCD predictions.

The backgrounds to the $(\gamma, W, Z)Z_2$ signals in the $Z_2 \rightarrow b\bar{b}$ channels arise from the $(\gamma, W, Z) g^*$ final states with a virtual gluon $g^*$ giving a $b\bar{b}$ pair. For the calculation of $p\bar{p} \rightarrow Wb\bar{b}$ we used the formulas in Ref. \cite{39}, while we used MADGRAPH \cite{40} to calculate $p\bar{p} \rightarrow Zb\bar{b}$ and $p\bar{p} \rightarrow \gamma b\bar{b}$. The differential cross sections $d\sigma/dm(b\bar{b})$ for the signals and backgrounds are shown in Figs. 6, 7, and 8 for $Wb\bar{b}$, $Zb\bar{b}$, and $\gamma b\bar{b}$ final states, respectively. While the background is a continuum in the $m(b\bar{b})$ spectrum, the signal gives a peak around the $Z_2$ mass. In Figs. 6(a), 7(a), and 8, the solid histogram is the SM background, while the long-dashed and short-dashed histograms show the effect of the additional $Z_2$ boson of mass 105 GeV and 85 GeV, respectively. Figure 6(b) and 7(b) show the corresponding signals and backgrounds for the SM Higgs boson of the same mass as the $Z_2$. Since the $Z_2$ is universally coupled, the cross sections for $c\bar{c}$ final states are the same as for $b\bar{b}$. If the UA2 bound of $\lambda \lesssim 1$ were weakened, larger $Z_2$ cross sections would be obtained with larger $\lambda$ values.

In Table 5 we present estimates of of the number of $Z_2 \rightarrow b\bar{b}$ signal and $b\bar{b}$ background
Table 5: Expected $Z_2 \rightarrow b\bar{b}$ signals and background event rates at the Tevatron with 100 pb$^{-1}$ luminosity and 100% detection efficiency, for $\Delta m(b\bar{b}) = \pm10$ GeV centered on $M_{Z_2} = 105$ GeV. A $Z_2$ coupling $\lambda = 1$ is assumed. The event numbers in parentheses are for acceptance cuts $p_T(b), p_T(\bar{b}) > 10$ GeV, $|\eta(b)|, |\eta(\bar{b})| < 2$, $|\cos \theta^*| < 2/3$, where $\theta^*$ is the angle of the $b$ with respect to the beam in the $b\bar{b}$ rest frame.

| s-channel $Z_2$ | Signal | Background |
|-----------------|--------|------------|
| $WZ_2$ (with $W \rightarrow e\nu, \mu\nu$) | $6 \times 10^4$ ($3 \times 10^4$) | $1.3 \times 10^7$ ($6 \times 10^5$) |
| $Z_1Z_2$ (with $Z_1 \rightarrow \nu\bar{\nu}$) | 9.6 | 6.1 |
| $Z_1Z_2$ (with $Z_1 \rightarrow e\bar{e}, \mu\bar{\mu}$) | 3.3 | 4.9 |
| $Z_1Z_2$ (with $Z_1 \rightarrow e\bar{e}, \mu\bar{\mu}$) | 1.1 | 1.7 |
| $\gamma Z_2$ | 80 | 120 |

events that would be expected at the Tevatron in an invariant mass bin $\Delta m(b\bar{b}) = \pm10$ GeV centered on $M_{Z_2} = 105$ GeV, assuming 100 pb$^{-1}$ luminosity and 100% detection efficiency. The signal event rates are at the interesting level for $Z_2$ discovery.

Summary

In summary, we have shown the following:

- A $Z'$ boson with baryonic couplings improves the overall fit to precision electroweak observables, including LEP and SLD measurements along with other low-energy measurements such as neutrino scattering. Our conclusion in this regard is in agreement with other recent analyses which were based on $Z$-pole observables only.

- The precision electroweak analysis constrains the product $\theta \lambda^{1/2}$ of the $Z, Z'$ mixing angle $\theta$ and the overall $Z'$ coupling strength $\lambda^{1/2}$.

- The electroweak analysis favors a light $Z_2$ mass, $M_{Z_2} \lesssim 200$ GeV. Values of $M_{Z_2}$ below the $Z$-mass are not ruled out.

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• The $s$-channel production rate of $Z_2$ in $p\bar{p}$ collisions is constrained by UA2 dijet measurements, with couplings up to $\lambda \sim 1$ allowed.

• The $Z_2$ can be produced in association with $\gamma, W, Z$, with cross sections at the Tevatron exceeding corresponding cross sections for $Z_1$ production in association with $\gamma, W, Z$.

• The $Z_2 \to b\bar{b}$ decay mode is an important signal for $Z_2$ production in association with $\gamma, W, Z$ at the Tevatron, giving a resonant enhancement in the $b\bar{b}$ invariant mass spectrum above the QCD background. These processes have a better signal-to-background ratio than the $s$-channel process.

• The $Z_2$ causes interference effects in $e^+e^- \to \bar{b}b(\bar{c}c)$ that may be observable at LEP 1.5. The interference contribution changes sign for $\sqrt{s}$ near $M_{Z_2}$ and is correlated with the signs of the deviations of $R_b(R_c)$ from SM predictions.

Acknowledgments

One of us (V.B.) thanks D. Amidei, D. Carlsmith, T. Han, J. Huston, W.-Y. Keung, and P. Mercadante for discussions. This research was initiated at the Institute for Theoretical Physics at Santa Barbara, whose support is gratefully acknowledged. This research was supported in part by the U.S. Department of Energy under Grants No. DE-FG02-95ER40896, No. DE-FG03-93ER40757, and No. DOE-EY-76-02-3071, in part by the National Science Foundation Grant No. PHY94-07194, and in part by the University of Wisconsin Research Committee with funds granted by the Wisconsin Alumni Research Foundation.

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Figures

1. The total cross section for the production of $p\bar{p} \rightarrow Z_2 \rightarrow jj$ at $\sqrt{s} = 630$ GeV for $\lambda = 0.3, 0.6, 1$. The UA2 90% CL upper limit on the production of a heavy boson decaying into 2 jets is shown.

2. The $b\bar{b}$ invariant mass distribution and the inclusive $p_T(b)$ distribution at the Tevatron, including the contribution of a $Z_2$ resonance, with $M_{Z_2} = 105$ GeV and $\lambda = 1$. The solid histogram denotes the SM background, including the $Z_1 \rightarrow b\bar{b}$ contribution. The dashed histogram includes the $Z_2$ contribution. The histograms at the bottoms of the figure are the $Z_2$ contributions alone. The acceptance cuts in Table 5 are imposed.

3. The $e^+e^- \rightarrow b\bar{b}(\bar{c}c)$ cross sections and the asymmetry $A_{FB}(b\bar{b})$ versus $\sqrt{s}$ in the vicinity of a $Z_2$ resonance of mass $M_{Z_2} = 105$ GeV, with $\lambda = 1$ and $\theta = -0.011$. The solid curve denotes the SM background. The dashed and dot-dashed curves include the contribution of an axial ($\gamma = 0$) and vector ($\gamma = \pi/2$) baryonic $Z'$, respectively.

4. The total cross sections for the production of $p\bar{p} \rightarrow WZ_2, ZZ_2, Z_2Z_2, \gamma Z_2$ (solid curves) at $\sqrt{s} = 1.8$ TeV. The cross sections for the standard model $WZ, ZZ, \gamma Z$ (squares) and $WH, ZH$ (dashed curves) production are also shown.

5. The cross sections for the production of $p\bar{p} \rightarrow WZ_2, ZZ_2, \gamma Z_2$ followed by $Z_2 \rightarrow b\bar{b}$ (solid curves) at $\sqrt{s} = 1.8$ TeV. The cross sections for the standard model $WZ, ZZ, \gamma Z$ with $Z \rightarrow b\bar{b}$ (squares) and $WH, ZH$ with $H \rightarrow b\bar{b}$ (dashed curves) production are also shown.

6. The $b\bar{b}$ invariant mass distribution $d\sigma/dm(b\bar{b})$ for $Wb\bar{b}$ final state. The solid histogram is the sum of the continuum $Wb\bar{b}$ and the SM $Z$ boson, while the long-dashed and short-dashed histograms show the additional $Z_2$ boson of mass 105 and 85 GeV, respectively. Part (b) is similar to part (a) with the additional $Z_2$ replaced by the SM Higgs boson.

7. The $b\bar{b}$ invariant mass distribution $d\sigma/dm(b\bar{b})$ for $Zb\bar{b}$ final state. The solid histogram is the sum of the continuum $Zb\bar{b}$ and the SM $Z$ boson, while the long-dashed and short-
dashed histograms show the additional $Z_2$ boson of mass 105 and 85 GeV, respectively. Part (b) is similar to part (a) with the additional $Z_2$ replaced by the SM Higgs boson.

8. The $b\bar{b}$ invariant mass distribution $d\sigma/dm(b\bar{b})$ for $\gamma b\bar{b}$ final state. The solid histogram is the sum of the continuum $\gamma b\bar{b}$ and the SM $Z$ boson, while the long-dashed and short-dashed histograms show the additional $Z_2$ boson of mass 105 and 85 GeV, respectively.
$v_s = 1.8 \, \text{TeV}$

$\mathbf{b\bar{b}}$ Cross Section

$\sigma(Z^2, b \rightarrow b\bar{b})$
$\frac{d\sigma}{dm(b\bar{b})}$ (pb/GeV)

Fig. 8

$\sqrt{s} = 1.8$ TeV

$\gamma Z_2(105 \text{ GeV}) + \gamma b\bar{b} + \gamma Z_1$

$\gamma b\bar{b}$ + $\gamma Z_1$

$\gamma Z_2(85 \text{ GeV})$ + $\gamma b\bar{b}$ + $\gamma Z_1$

$m(b\bar{b})$

0.001 0.01 0.1 0.01 0.1 0.1