In the Standard Model of particle physics, the masses of the fundamental fermions and bosons are generated by the Higgs mechanism. Via this mechanism, the particle masses result from their interaction with an external scalar field known as the Higgs field.

In a recent paper [1], it was pointed out that high mass particles can be used as detectors of the Higgs field. This possibility arises because high mass particles constitute significant sources of the Higgs field and the resulting source-modified field can be detected by other high mass particles that suffer induced mass shifts.

In this paper explicit quantitative details are presented on the size of the effect in the cases of the $Z$ mass in the $Z Z$ threshold region, the $W$ mass in the $W W$ threshold region and the $t$ mass in the $t t$ threshold region [25].

An overview is also given of the current status of $W$, $Z$ and $t$ mass determinations in different production environments.

The relevant formula from [1] is equation (19), giving:

$$\Delta M_X \approx -\Gamma_X \left( \frac{M_X^2}{2\pi v^2} \right) \times \left( \frac{M_X^2}{M_{XX}} \right) \sqrt{\frac{1}{M_{XX}^2 - 4M_X^2}} \times \ln \left[ \frac{M_X}{\Gamma_X} \right].$$

(1)

Where $M_X$ and $\Gamma_X$ are the mass and width of either $Z$, $W$ or $t$, $M_{XX}$ is the effective mass of the $Z Z$, $W W$ or $t t$ pair and $v$ is the Higgs vacuum expectation value ($= 246$ GeV). Here, all masses and widths are expressed in GeV/$c^2$. The minus sign indicates that the mass of particle $X$ determined in the pair environment is always lower than the corresponding mass determined for particle $X$ produced alone. Note that, in the notation of [1], particles 1 and 2 are identical and therefore $M_1 = M_2$.

This expression provides the shift in mass of particle $X$ as a function of the effective mass of the pair of particles, $M_{XX}$. As the $XX$ threshold is approached, $M_{XX}$ approaches $2M_X$. The following three figures show the size of the effect in the cases of $Z$, $W$ and $t$, respectively. As can be seen, the predicted mass shifts are large and significant and they should be detectable.

The following figure (Fig. 1) shows the $Z$ mass shift as a function of the effective mass of the $Z Z$ pair. The $Z Z$ threshold is at 182.375 GeV/$c^2$ and in the region within 100 MeV/$c^2$ of this threshold the mass shift is always larger than 1.5 GeV/$c^2$. The effective mass of the $Z$ pair has to be more than 17 GeV/$c^2$ above threshold before the $Z$ mass shift goes below 100 MeV/$c^2$.

FIG. 1: The $Z$ mass shift plotted against the $Z Z$ effective mass in the $Z Z$ threshold region.
The $W$ mass shift as a function of the effective mass of the $WW$ pair is presented in Figure 2. The $WW$ threshold is at 160.820 GeV/c$^2$ and in the region within 100 MeV/c$^2$ of this threshold the mass shift is always larger than 0.9 GeV/c$^2$. The value of $M_{WW}$ has to be almost 8 GeV/c$^2$ above threshold before the $W$ mass shift goes below 100 MeV/c$^2$.

![FIG. 2: The $W$ mass shift plotted against the $WW$ effective mass in the $WW$ threshold region.](image1)

The mass of the $Z$-boson has been determined very precisely at LEP1 [3, 4, 5, 6]. The results are summarized in Table I. These are all measurements made at the $Z$-pole and the average value is $M_Z = 91.1875 \pm 0.0021$ GeV/c$^2$ [7].

| Experiment       | $M_Z$ GeV/c$^2$ | Reference |
|------------------|-----------------|-----------|
| ALEPH - LEP1     | 91.1893 ± 0.0031| [3, 4]    |
| DELPHI - LEP1    | 91.1863 ± 0.0028| [4, 7]    |
| L3 - LEP1        | 91.1894 ± 0.0030| [5, 6]    |
| OPAL - LEP1      | 91.1853 ± 0.0029| [6, 7]    |
| Average          | 91.1875 ± 0.0021| [7]       |

TABLE I: $Z^0$ mass determinations at the $Z^0$-pole.

All four LEP experiments saw clear $Z$ signals in the $ZZ$ channel at LEP2, but none published a separate $Z$ mass determination [8, 9, 10, 11]. However, all four experiments are consistent with the LEP2 $Z$ mass being the same as the LEP1 $Z$ mass.

Figure 4 shows the expected $Z$ mass shift (upper curve) as a function of the LEP2 center-of-mass energy ($E_{CM}$). As noted earlier, $\Delta M_Z$ is larger than 100 MeV/c$^2$ until $E_{CM}$ reaches $\sim 200$ GeV; the weighted average for the $Z$ mass shift over the entire LEP2 energy range is $\sim 140$ MeV/c$^2$. It would be very interesting to see a $Z$-candidate mass plot for the lowest energy data point at $E_{CM} = 182.7$ GeV where the mass shift is predicted to be greater than 800 MeV/c$^2$ and $M_Z \sim 90.3$ GeV/c$^2$.

![FIG. 4: The $Z$ (squares) and $W$ (diamonds) mass shifts plotted against the LEP center-of-mass energy.](image2)

The mass of the $W$-boson has been determined quite precisely at LEP2 [12, 13, 14, 15]. All of these measurements have been made in an environment where the $W$ is one of a $WW$ pair. Table II summarises the current

![FIG. 3: The $t$ mass shift plotted against the $tt$ effective mass in the $tt$ threshold region.](image3)
The average of these measurements gives \( M_W = 80.392 \pm 0.039 \text{ GeV}/c^2 \). The mass of the W-boson has also been determined quite precisely at the Tevatron collider \(^{17, 18}\), where it is produced alone, and Table II again summarises the situation. Here the average of the \( W \) mass measurements is \( M_W = 80.452 \pm 0.059 \text{ GeV}/c^2 \). These two \( M_W \) determinations give the same result within errors and they can be combined to give the global average, \( M_W = 80.410 \pm 0.032 \text{ GeV}/c^2 \), presented in Table III \(^{16}\). In light of Figure 3 it is perhaps not surprising that the LEP2 and Tevatron determinations of \( M_W \) are in good agreement (within the \( \sim 70 \text{ MeV}/c^2 \) combined error); the expected \( W \) mass shift is below 50 MeV/c\(^2\) for most of the LEP2 data and the first two energy points, where the predicted mass shift is large, constitute \( < 2\% \) of the total data set. Again it would be very interesting to see the value of \( M_W \) determined for the lowest energy data point at \( E_{CM} = 161.3 \text{ GeV} \) where the mass shift is predicted to be greater than 400 MeV/c\(^2\) and \( M_W \sim 80.0 \text{ GeV}/c^2 \).

| Experiment                  | \( M_W \text{ GeV}/c^2 \) | Reference |
|-----------------------------|---------------------------|-----------|
| ALEPH - LEP2                | 80.379 \pm 0.058          | 12, 16    |
| DELPHI - LEP2               | 80.404 \pm 0.074          | 13, 16    |
| L3 - LEP2                   | 80.376 \pm 0.077          | 14, 16    |
| OPAL - LEP2                 | 80.416 \pm 0.053          | 15, 16    |
| LEP2 Average                | 80.392 \pm 0.039          | 16        |
| CDF - Tevatron Collider     | 80.433 \pm 0.079          | 17        |
| DØ - Tevatron Collider      | 80.483 \pm 0.084          | 18        |
| PP Collider Average         | 80.452 \pm 0.059          | 19        |
| Global Average              | 80.410 \pm 0.032          | 16        |

TABLE II: \( W^\pm \) mass determinations in the \( W^\pm \) pair environment.

The mass of the \( W \) has been determined in other situations where it is not part of a pair. These are all indirect determinations. In neutrino-nucleon scattering experiments, the most significant of these is from a careful measurement of \( \sin^2\theta_W \) by the NuTeV collaboration \(^{20}\) and, assuming the value of \( M_Z \) from Table I it gives \( M_W = 80.136 \pm 0.084 \text{ GeV}/c^2 \). The LEP Electroweak Working Group has also determined \( M_W \) from a global standard model fit to the SLD data, LEP1 data and the best measurement of \( M_t \). They quote \( M_W = 80.364 \pm 0.021 \text{ GeV}/c^2 \).

The \( t \) mass has been determined by CDF \(^{21}\) and DO \(^{22}\) and the combined average value \(^{22}\) is \( M_t = 172.7 \pm 2.9 \text{ GeV}/c^2 \). The \( t \)'s are presumably produced in pairs. There is no determination to date of \( M_t \) in an environment where the \( t \) is produced alone. The current status of top quark measurements from the Tevatron Electroweak Working Group can be found at \(^{24}\). It would be interesting to investigate very carefully the events where the \( t\bar{t} \) effective mass is close to threshold: for example, at 10, 20, 30, 40 and 50 GeV/c\(^2\) above threshold, the \( t \) mass is predicted to be shifted down by 330, 360, 290, 240 and 200 MeV/c\(^2\), respectively.

The calculations of reference \(^{1}\) indicate that the Standard Model, with no extensions, predicts that masses of particles can depend on whether or not they are produced singly or in pairs. This paper demonstrates that the predicted mass differences can be large near threshold and suggests that for events in which the kinematics is well-enough defined, there may be interesting constraints on Higgs physics from \( ZZ \), \( WW \) and \( t\bar{t} \) production. In particular, the \( ZZ \) channel could provide a powerful test of the prediction, especially with one \( Z \) decaying to \( e^+e^- \) and the other to \( \mu^+\mu^- \) with all 4-vectors well measured. Even for a few fortuitous events close to threshold one might hope to see a significant mass shift. With the full data set, the mass shift trend might be visible in a plot of \( M_Z \) as a function of \( M_{ZZ} \).

For \( WW \) events and \( t\bar{t} \) events there are additional complications due to electromagnetic and strong interactions \(^{12}\), but again the data should be looked at with a mind open to the possibility of mass shifts.

Because the leading part of the effect is independent of Higgs mass, failure to see the predicted effect could rule out the Higgs mechanism in the Standard Model for all possible Higgs masses. Observation of the mass shift would provide strong evidence for the idea of dynamically generated masses via coupling to the Higgs field.

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[1] S. Reucroft, Y. N. Srivastava, J. Swain and A. Widom, “Probing the Higgs Field Using Massive Particles as Sources and Detectors”, submitted to Phys. Rev. and hep-ph/0509151 (2005).
[2] G. Castellani, S. Reucroft, Y. N. Srivastava, J. Swain, and A. Widom, “Final State Interactions and the Effects of Potentials on Particle Reactions”, hep-ph/0509089 (2005).
[3] R. Barate et al. (ALEPH Collaboration), Euro. Phys. J. C14 (2000) 1.
[4] P. Abreu et al. (DELPHI Collaboration), Euro. Phys. J. C16 (2000) 371.
[5] M. Acciarri et al. (L3 Collaboration), Euro. Phys. J. C16 (2000) 1.
[6] G. Abbiendi et al. (OPAL Collaboration), Euro. Phys. J. C19 (2001) 587.

[7] The ALEPH, DELPHI, L3, OPAL, SLD Collaborations, the LEP Electroweak Working Group, the SLD Electroweak and Heavy Flavour Groups, “Precision Electroweak Measurements on the Z Resonance” and references cited therein, CERN-PH-EP/2005-041, SLAC-R-747, submitted to Physics Reports and hep-ex/0509008 (September, 2005).

[8] H. Li et al. (ALEPH Collaboration), ALEPH-2001-006 (2001); R. Barate et al. (ALEPH Collaboration), Phys. Lett. B469 (1999) 287.

[9] J. Abdallah et al. (DELPHI Collaboration), Euro. Phys. J. C30 (2003) 447.

[10] P. Achard et al. (L3 Collaboration), Phys. Lett. B581 (2004) 19; P. Achard et al. (L3 Collaboration), Phys. Lett. B572 (2003) 133; M. Acciarri et al. (L3 Collaboration), Phys. Lett. B497 (2001) 23.

[11] G. Abbiendi et al. (OPAL Collaboration), Euro. Phys. J. C32 (2003) 303; G. Abbiendi et al. (OPAL Collaboration), Phys. Lett. B476 (2000) 256.

[12] R. Barate et al. (ALEPH Collaboration), Euro. Phys. J. C17 (2000) 241.

[13] P. Abreu et al. (DELPHI Collaboration), Phys. Lett. B511 (2001) 159.

[14] M. Acciarri et al (L3 Collaboration), Phys. Lett. B454 (1999) 386.

[15] G. Abbiendi et al. (OPAL Collaboration), submitted to Euro. Phys. J. and hep-ex/0508060 (2005); G. Abbiendi et al. (OPAL Collaboration), Phys. Lett. B507 (2001) 29.

[16] The LEP Collaborations, ALEPH, DELPHI, L3, OPAL and the LEP Electroweak Working Group, “A Combination of Preliminary Electroweak Measurements and Constraints on the Standard Model” and references cited therein, CERN-PH-EP/2005-XXX, LEPEWWG2005-01, ALEPH 2005-004 PHYSICS 2005-004, DELPHI 2005-027-PHYS-947,L3 Note 2832,OPAL PR-413 and hep-ex/0511027 (November, 2005).

[17] T. Affolder et al. (CDF Collaboration), Phys. Rev. D64 052001 (2001).

[18] V. M. Abazov et al. (DØ Collaboration), Phys. Rev. D66 012001 (2002).

[19] http://www.cern.ch/LEPEWWG

[20] G.P. Zeller et al. (NuTeV Collaboration), Phys. Rev. Lett. 88 (2002) 091802; Erratum-ibid. 90 (2003) 239902.

[21] http://www-cdf.fnal.gov/physics/new/top/top.html

[22] http://www-d0.fnal.gov/Run2Physics/WWW/

[23] The CDF Collaboration, the DØ Collaboration, and the Tevatron Electroweak Working Group, “Combination of CDF and DØ Results on the Top-Quark Mass”, hep-ex/0507091 (July, 2005).

[24] http://tevewwg.fnal.gov/top/

[25] In an obvious notation, $W$ is used to represent $W^\pm$, $Z$ to represent $Z^0$ and $t$ to represent the $t$-quark.