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Probing the Higgs field using massive particles as sources and detectors

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Abstract. In the standard model, all massive elementary particles acquire their masses by coupling to a background Higgs field with a non-zero vacuum expectation value. What is often overlooked is that each massive particle is also a source of the Higgs field. A given particle can in principle shift the mass of a neighboring particle. The mass shift effect goes beyond the usual perturbative Feynman diagram calculations which implicitly assume that the mass of each particle is rigidly fixed. Local mass shifts offer a unique handle on Higgs physics since they do not require the production of on-shell Higgs bosons. We provide theoretical estimates showing that the mass shift effect can be large and measurable, especially near pair threshold, at both the Tevatron and the LHC.

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1 Introduction

In the usual treatments of a Poincaré invariant field theory, particles are labelled according to irreducible representations of the space-time symmetry group, and labelled according to values of two Casimir invariants which can be constructed from spin and mass [1]. Within this framework, it is common practice in high energy physics to view the mass of a particle, just as its spin, as an intrinsic and immutable property completely unaffected by its surroundings.

That being said, in the standard model [2] "mass" is more than just a representation label with no more dependence on any external fields than the spin of a particle. In fact, all of the usual *elementary* fermions and bosons (except for the Higgs boson itself) are, in the absence of interactions, *massless*. That is, there is no single non-dynamical parameter that appears as a mass term for any of the fermions or gauge bosons in the standard model Lagrangian. Rather, there is an emergent mass through a coupling to a scalar field whose dynamics have been arranged for it to have a non-zero value which is independent of space and time (i.e. to preserve the Poincaré symmetry of space-time). Couplings to this field, assumed constant in space and time due to the dynamics of the theory, play the roles of masses.

Of course actual experiments need not be Poincaré invariant, and in general the presence of an experimental setup will break this invariance. In condensed matter physics, one often needs to consider the effects of an environment, and a new mass (shifted by electromagnetic interactions with matter, for example, and not necessarily even a scalar any longer) must often be introduced [3], together with a different symmetry group. Even outside bulk condensed matter, electromagnetic mass shifts are commonly introduced in the literature due either to external fields [4, 5] or even to changes in the vacuum fluctuations due to boundaries [6]. In nuclear physics similar phenomena occur. For example, a free neutron is unstable but, when bound to a proton in a deuteron, it becomes stable since it is then effectively too light to decay. In each case one can think of mass as being due to two parts: one somehow "intrinsic" and one due to interaction with an external field.

As stated earlier, in the standard model [2] these ideas are taken to an extreme so that even in the vacuum *all* of the mass of the fermions and gauge bosons is due to interaction with an external field – the Higgs field – which is taken to have a non-vanishing vacuum expectation value.

While for many applications the background Higgs field can be considered a space-time constant, the standard model asserts that the Higgs field is a dynamical object. Indeed, if it were not, then there would be no way to tell that it exists at all! Approaches so far [7] to detecting the Higgs field have concentrated on looking for its quanta: Higgs bosons. One hope is that accelerators will have enough energy to produce a particle on

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shell, but so far all that has been done is to rule out a Higgs with a mass below 114.4 GeV/c^2 at 95% confidence level.

Another approach is to look for measurable quantities involving Higgs boson exchange between heavy particles that could reveal its existence via radiative corrections. A recent best fit result [8] from radiative corrections gives, with large errors, a Higgs mass of 168 GeV/c^2 for an assumed top quark mass of 178 GeV/c^2, placing detection of an on-shell Higgs boson likely out of reach of the Tevatron at Fermilab and leaving its discovery to the LHC at CERN. The LEP Electroweak Working Group makes its most recent analyses of combined data available at [9]. Their preferred value for the Higgs mass is 85 GeV/c^2, with an experimental uncertainty of +39 and −28 GeV/c^2 (at 68% confidence level, not including theoretical uncertainty). This rather large and asymmetric uncertainty is due to the fact that in typical radiative corrections the Higgs mass appears only logarithmically so in fact even quite high Higgs masses of hundreds of GeV/c^2 are not ruled out.

Fortunately, the notion of a dynamical Higgs field leads one to another approach that has not yet been suggested to the best of our knowledge: to probe the Higgs field not directly in terms of its quanta, but rather as a field which changes masses. The field is sourced to a significant extent by heavy particles (ones which couple strongly to the Higgs field) and the resulting source-modified Higgs field might then be detected by *other* heavy particles via induced mass shifts.

The *static* Higgs field σ at a spatial point $\mathbf{r}$, $\sigma(\mathbf{r})$, produced by a particle of mass m fixed at rest on the coordinate origin is given by

$$\sigma(\mathbf{r}) = -\left(\frac{mc}{4\pi\hbar v}\right)\frac{e^{-m_{\mathrm{H}}cr/\hbar}}{r}\,, \tag{1}$$

where the vacuum expectation value of the Higgs field without the source is $v = \langle\phi\rangle$, the total Higgs field is $\phi = v + \sigma$ and m_{H} is the Higgs mass. The rapid falloff with distance for a Higgs boson mass of a few hundred GeV/c^2, together with the weakness of the Higgs coupling to all but the most massive particles makes it difficult to suggest suitable laboratory experiments to examine Higgs-induced mass shifts. One hopeful situation is the production of one massive particle together with a second massive particle. Let us consider this case in detail.

2 The mass of a particle in the presence of another

The source of the Higgs field is the trace of the energy-pressure tensor which may be formally computed by differentiating the lagrangian density with respect to the elementary particle masses of the model

$$T^{\mu}_{\mu}(x) \equiv T(x) = \sum_a m_a \frac{\partial \mathcal{L}(x)}{\partial m_a}\,. \tag{2}$$

Thus, a fermionic or bosonic source of the Higgs field would have the form

$$\begin{aligned} T_{\mathrm{fermion}}(x) &= -c^2 m_{\mathrm{F}}\bar{\psi}(x)\psi(x)\,, \\ T_{\mathrm{boson}}(x) &= -\left(\frac{m_B^2 c^3}{\hbar}\right)\bar{B}(x)B(x)\,. \end{aligned} \tag{3}$$

For a *classical particle* with the proper time action $S_{\mathrm{classical}} = -mc^2\int \mathrm{d}\tau$, the lagrangian density $\mathcal{L}_{\mathrm{classical}}(x) = -mc^3\int \delta\big(x - x(\tau)\big)\,\mathrm{d}\tau$ yields the classical source

$$T_{\mathrm{classical}}(x) = -mc^3\int \delta\big(x - x(\tau)\big)\,\mathrm{d}\tau\,. \tag{4}$$

The idea now is very simple. Consider a massive particle "1" of mass m_1 adjacent (in a space-time picture) to another particle "2" of mass m_2. Here m_1 and m_2 refer to their masses in the usual sense of a Yukawa coupling times the background Higgs vacuum expectation value. The claim is that particle 1 will couple to the Higgs field produced by fermion 2 and have its mass shifted by an amount proportional to its own mass m_1 (its coupling to the Higgs fields) and also proportional to m_2 (the strength of particle 2's coupling to the Higgs field). The relevant Higgs mass shift coupling strength may be written

$$\alpha_{\mathrm{H}} = \frac{c^2 m_1 m_2}{4\pi\hbar^2 v^2} = \frac{\sqrt{2}G_{\mathrm{F}} m_1 m_2}{4\pi\hbar c} \tag{5}$$

where G_{F} is the Fermi coupling strength. The relevant energy scale is $(\hbar v/c) \approx 246$ GeV so that only heavy particle pairs, e.g. W^+W^-, ZZ, or $\bar{t}t$, have an appreciable mutual coupling strength.

It turns out that the mass shift is only weakly dependent on the Higgs particle mass in that the light cone singularity of the Higgs propagator for neighboring events is mass independent. No real (on-shell) Higgs boson needs to be produced for the mass shift any more than a real photon needs to be produced to provoke an electromagnetic Lamb energy shift, or a real pion needs to be produced to make a neutron in a deuteron stable. In detail, the propagator

$$D(x-y) = \int \left[\frac{e^{\mathrm{i}k(x-y)}}{k^2 + \kappa^2 - \mathrm{i}0^+}\right]\frac{d^4k}{(2\pi)^4}\,, \tag{6}$$

(where $\hbar\kappa = m_{\mathrm{H}}c$) determines the Higgs field at particle 2 due to particle 1 as given by

$$\sigma_2(x) = \frac{1}{\hbar c v}\int D(x-y)T_1(y)d^4y\,. \tag{7}$$

For example if particle 1 moves on a path $x_1(\tau_1)$, then (4) and (7) imply

$$\sigma_2(x) = -\frac{m_1 c^2}{\hbar v}\int D\big(x - x_1(\tau_1)\big)\,\mathrm{d}\tau_1\,. \tag{8}$$

If particle 2 moves on a path $x_2(\tau_2)$, then the added action to particle 2 due to particle 1 is

$$S_{21} = \frac{1}{cv}\int T_2(x)\sigma_2(x)d^4x\,,$$
$$S_{21} = -\frac{m_2c^2}{v}\int \sigma_2\big(x_2(\tau_2)\big)\,\mathrm{d}\tau_2\,,$$
$$S_{21} = \frac{m_1m_2c^4}{\hbar v^2}\int\int D\big(x_1(\tau_1)-x_2(\tau_2)\big)\,\mathrm{d}\tau_1\,\mathrm{d}\tau_2\,. \quad (9)$$

Here it is of use to recall the Feynman–Wheeler formulation of electrodynamics in which the interaction between two point charges has the form

$$S_{21}(\text{photon}) = \frac{e_1e_2}{c}\int_{P_1}\int_{P_2} D_{\mu\nu}(x_1-x_2)[\mathrm{d}x_1^\mu\,\mathrm{d}x_2^\nu]\,. \quad (10)$$

P_1 is the path of charge 1, P_2 is the path of charge 2 and $D_{\mu\nu}$ is the photon propagator. The Higgs exchange analog to the Feynman–Wheeler interaction has been derived in (9); It is

$$S_{21} = \frac{\sqrt{2}G_\mathrm{F}m_1m_2}{c}\int_{P_1}\int_{P_2} D(x_1-x_2)[c\,\mathrm{d}\tau_1 c\,\mathrm{d}\tau_2]\,. \quad (11)$$

To compute the mass shifts for the two particles due to their mutual interactions when mass m_1 travels on path P_1 and mass m_2 travels along path P_2 one need only apply the rule

$$\mathfrak{Re}\,e\big(S_{21}\big) = -c^2\Delta m_1\int_{P_1}\mathrm{d}\tau_1 = -c^2\Delta m_2\int_{P_2}\mathrm{d}\tau_2\,. \quad (12)$$

In particular, the mass shift in particle 2 due to the Higgs field produced by particle 1 is given by

$$\Delta m_2 = -\left(\frac{\sqrt{2}G_\mathrm{F}m_1m_2}{c}\right) \times \frac{\int_{P_1}\int_{P_2}\mathfrak{Re}\,eD\big(x_1-x_2\big)\,\mathrm{d}\tau_1\,\mathrm{d}\tau_2}{\int_{P_2}\mathrm{d}\tau_2}\,. \quad (13)$$

Suppose that particles 1 and 2 have the four momenta $p_1 = m_1v_1$ and $p_2 = m_2v_2$ (where v_1 and v_2 are four-velocities) and thus the invariant mass $\sqrt{s}$ as given by

$$-c^2s = (p_1+p_2)^2\,,$$
$$-\left(\frac{v_1\cdot v_2}{c^2}\right) = \frac{s-(m_1^2+m_2^2)}{2m_1m_2}\,. \quad (14)$$

The real part of the Higgs propagator $\mathfrak{Re}\,eD(x-y)$ vanishes if x and y are space-like separated. If x and y are not space-like separated, then $\mathfrak{Re}\,eD(x-y)$ has two terms: (i) There is a light-cone singularity which is independent of the Higgs mass. (ii) There is a finite smooth portion which depends on the Higgs mass $m_\mathrm{H} = (\hbar\kappa/c)$. In terms of the first order Bessel function $J_1(\xi)$ we have

$$\mathfrak{Re}\,eD(x) = 0 \quad \text{for space-like} \quad x^2>0\,,$$
$$\mathfrak{Re}\,eD(x) = \frac{1}{4\pi}\left[\delta(x^2) - \frac{\kappa J_1\big(\kappa\sqrt{-x^2}\big)}{2\sqrt{-x^2}}\right] \quad x^2\le 0\,. \quad (15)$$

The light-cone singularity dominates the mass shift in (13).

The proper time integral lasts (on average) as long as the particle life-time $\int \mathrm{d}\tau_2 = \Gamma_2^{-1}$ so that the light-cone singularity approximation in (13) reads

$$\frac{\Delta m_1}{\Gamma_1} \approx -\left(\frac{\sqrt{2}G_\mathrm{F}m_1m_2}{4\pi c}\right) \times \int\int \delta\big((v_1\tau_1 - v_2\tau_2)^2\big)\,\mathrm{d}\tau_1\,\mathrm{d}\tau_2\,, \quad (16)$$

where $4\pi\mathfrak{Re}\,D(x_1-x_2) \approx \delta\big((x_1-x_2)^2\big)$ has been invoked and, of course, $(\Delta m_1/\Gamma_1) = (\Delta m_2/\Gamma_2)$. The double integral on the right hand side of (16) has a logarithmic singularity of the form

$$c^2\int\int\delta\big((v_1\tau_1-v_2\tau_2)^2\big)\,\mathrm{d}\tau_1\,\mathrm{d}\tau_2 \approx \times \frac{1}{\sqrt{(v_1\cdot v_2/c^2)^2-1}}\ln\left(\frac{\tau_\mathrm{max}}{\tau_\mathrm{min}}\right)\,. \quad (17)$$

The maximum and minimum proper times (τ_max and τ_min) must now be estimated, but as they only appear logarithmically, our results depend only weakly on how this is done. The maximum proper time τ_max is determined by particle life-times $\tau_\mathrm{max} \sim \Gamma^{-1}$. The minimum proper time is determined by the duration of the classical path viewpoint $\tau_\mathrm{min} \sim (\hbar/mc^2)$. We then estimate $(\Delta m_1/\Gamma_1)$ as

$$\left(\frac{\Delta m_1}{\Gamma_1}\right) \approx -\left(\frac{\sqrt{2}G_\mathrm{F}m_1m_2}{4\pi c^3}\right) \times \frac{1}{\sqrt{(v_1\cdot v_2/c^2)^2-1}}\ln\left[\frac{c^2(m_1+m_2)}{\hbar(\Gamma_1+\Gamma_2)}\right]\,. \quad (18)$$

In terms of the invariant mass $\sqrt{s}$, (18) reads

$$\frac{c^2\Delta m_1}{\hbar\Gamma_1} \approx -\left(\frac{c^2m_1m_2}{2\pi\hbar^2v^2}\right) \times \sqrt{\frac{m_1^2m_2^2}{s^2-2s(m_1^2+m_2^2)+(m_1^2-m_2^2)^2}} \times \ln\left[\frac{c^2(m_1+m_2)}{\hbar(\Gamma_1+\Gamma_2)}\right]\,. \quad (19)$$

Equation (19) is the central theoretical result of this work. As can easily be seen, at least near threshold, the right hand side is the product of terms of order unity so the effect need not be small!

An immediate consequence of the predicted mass shifts is, of course, also a change in widths. To a good leading approximation, most heavy particles of interest such as t, W, Z decay mainly into two bodies. In these cases the phase space is proportional to the 3-momenta of the outgoing particles. As is well-known, this is proportional to $\sqrt{\lambda(m_A^2, m_B^2, m_C^2)}/m_A$ where A represents the heavy particle, B and C its decay products, and $\lambda(x,y,z) = x^2 + y^2 + z^2 - 2xy - 2yz - 2zx$. In most cases (the main exception being $t \to Wb$) the outgoing particles can be considered almost massless and the width of a Z or W is proportional to its mass. In either case, the change $\Delta\Gamma$ in width Γ is easily obtained and seen to be large, i.e. $(\Delta\Gamma/\Gamma) \approx (\Delta M/M)$.

3 Experimental comments

The key experimental message that we wish to communicate in this paper is that if one is to produce heavy particles (where "heavy" means with mass not small compared to $246\,\mathrm{GeV/c^2}$) in conjunction with other heavy particles, there is good information in the measured distribution of masses and widths as a function of relative velocities (or center of mass energy) as these need not be the same as one would expect from single production. This gives information on the structure of the Higgs field produced by heavy particles *even if there is not enough energy to produce an on-shell Higgs boson*. In particular, this means that kinematical fits using as input masses obtained from other experiments, where heavy particles are singly produced, should not be done without great care. It also means that mass cuts and other kinematical cuts obtained from experiments where heavy particles are singly produced, are not necessarily reliable if other heavy particles are produced in association.

A concrete example of how data might be approached is perhaps in order. Suppose one is looking at the production of Z-boson pairs. We take this example since the many other concerns about final state interactions can be neglected: there are no one-gluon or one-photon exchange potentials and Yukawa potential effects [10]. If each Z boson decays into e^+e^- or $\mu^+\mu^-$ one has access to the full kinematics in a rather clean environment. With the invariant masses of e^+e^- and $\mu^+\mu^-$ plotted as a function of relative velocity or center of mass energy between the Z's, and with enough statistics, the predicted mass shift could be detectable.

Even in the absence of a more reliable theoretical estimate of all factors involved at this moment, the data are certainly worth looking at with an open mind (and relaxed cuts and no kinematical mass fits).

There are several processes that can be investigated experimentally and that have the potential to see the effect described in this paper. These are Z^0Z^0 versus single Z^0 production, W^+W^- versus single $W^\pm$ production and $t\bar{t}$ versus single t production. In addition, a measurement of the mass of these particles near pair threshold can be compared to the mass when the particles are far from pair threshold.

The mass of the Z^0-boson has been determined very precisely at LEP1 [11–14] yielding the result [15] $M_Z = 91.1876 \pm 0.0021\,\mathrm{GeV/c^2}$. These are all measurements made at the Z^0 pole. All four LEP experiments saw clear Z^0 signals at LEP2, but none made a separate Z^0 mass determination [16–22]. All four experiments are consistent with M_Z being independent of production mechanism (with an uncertainty of $\lesssim 1\%$); it is clear from the cross-section data that the Z^0Z^0 threshold is close to 180 GeV.

The mass of the $W^\pm$-boson has been determined quite precisely at LEP2 [23–26] and at the Tevatron collider [27, 28]. The average of all these measurements [9, 15] gives $M_W = 80.425 \pm 0.034\,\mathrm{GeV/c^2}$.

In addition, indirect determinations of the W mass have been made. One of these is from a careful measurement of $\sin^2\theta_W$ by the NuTeV collaboration [29, 30] and, assuming the value of M_Z from LEP1, gives $M_W = 80.136 \pm 0.084\,\mathrm{GeV/c^2}$. 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 [9]. They quote $M_W = 80.373 \pm 0.023\,\mathrm{GeV/c^2}$.

The t mass has been determined by CDF [31] and D$\emptyset$ [32] and the combined average value at the time of writing [33] is $m_\mathrm{t} = 172.7 \pm 2.9\,\mathrm{GeV/c^2}$. 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, although such a measurement is important because the t-quark could potentially provide the most sensitive probe of the Higgs field. The current status of top quark measurements from the Tevatron Electroweak Working Group can be found at [34]. It would be interesting to investigate very carefully the events where the $t\bar{t}$ effective mass is close to threshold.

While the data published to date do not contain enough information on the event kinematics in order to establish the effect we describe here, we hope that this paper will stimulate further analyses. In particular, it makes sense to study the masses determined for particles produced in pairs near and far from threshold, or even better, as a function of center-of-mass energy. Single production and pair production well above threshold should give masses in good agreement with each other, and corresponding to the usual notion of the "mass" of a particle. Masses obtained from pairs near threshold could be significantly lower.

Of course there is always danger in attempting to reanalyse or reinterpret published data in light of a new way of thinking about the analysis, and references here to published data are meant only to describe the current state of the art and not to claim evidence for or against the predicted effect. Data are always analysed with certain theoretical expectations in place and they can affect published results in ways that are impossible to judge without access to the original data. For example, one might well reject candidate Z^0Z^0 events on the basis of a low reconstructed Z mass relative to expectations from singly-produced Z bosons at LEP, while in fact such events could show evidence for a Higgs-induced mass reduction! These considerations are of even greater importance for heavier particles such as the top quark and anything still heavier but not yet discovered that might be produced at future accelerators.

4 A note on Mach's principle

Finally, it is interesting to note the distinctly Machian nature of this result: the mass of a particle is due, at least in part, to its interactions with all other particles. This reflects a greater degree of background independence of the standard model [35] than is usually considered, since not only the background Higgs field but in fact all the local masses are to some extent dynamically determined. The fact that masses are *reduced* due to interactions with a scalar (and thus attractive) field produced by surrounding particles would seem, however, to offer little hope for a Machian picture of a scalar interaction being responsible for the inertial mass of an object which would be thought of as intertialess in an empty universe. A similar conclusion might seem to follow for the attractive spin-2 force associated with gravitation, however this line of reasoning lies firmly within linearised general relativity and requires more careful consideration.

5 Conclusions

The standard model predicts that particles not only obtain their masses from coupling to a background Higgs field, but that they themselves are the sources of a Higgs field which can modify the masses of nearby particles. While a full calculation contains many subtleties, its sign is unambiguous, and reasonable estimates of the effect in the production of pairs of heavy particles are that the effect can be very large, especially near threshold. An additional feature of the effect which is quite appealing in terms of whether the Higgs mechanism is indeed responsible for mass or not is that the predicted effect, at least close to threshold in pair production, is largely independent of Higgs mass. In other words, failure to observe the effect could rule out a Higgs boson of any mass at all, even well-beyond the reach of the LHC after many years of running. On the other hand, observation of the effect would lend strong direct experimental support to the existence of a Higgs boson while leaving its actual mass largely undetermined without a careful study of the center-of-mass energy dependence of the effect.

While completely within the standard model, this new effect is beyond the usual perturbative Feynman diagram calculations and thus, although straightforward physically, seems to have escaped notice so far. The $W^{\pm}$ and Z^0 bosons have both been observed in environments where they are produced singly or in pairs and could offer some information on the Higgs sector of the standard model of a nature different from direct searches for on-shell particles and radiative corrections assuming fixed particle masses. Future analyses with top quarks offer even more information.

Experimental analyses invariably make assumptions about the nature of what is being observed. Now that the case has been made that masses – until now thought to be independent of production mechanism – may in fact vary, the possibility of new information from old data begins to open up. One simple fact which already may be in conflict with published data so far, albeit at low statistical significance, is that on general grounds, one expects that heavy particles produced in pairs will be less massive than ones which are singly produced. Just how much, of course, depends on kinematical details which are not easy to extract from published data.

The experimental situation is both tantalizing in light of data which exist now, and very promising with the expectation of more relevant data both from the Tevatron and the LHC. Of course a high luminosity linear collider which could scan the energy regions of interest near threshold for pair production of various heavy particles would also be of great interest.

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References

1. S. Weinberg, The Quantum Theory of Fields, Vol. 1: Foundations (Cambridge University Press, Cambridge, 1995)
2. M.E. Peskin, D.V. Schroeder, An Introduction to Quantum Field Theory (Addison-Wesley, Reading, MA, 1995)
3. J.C. Slater, Phys. Rev. **76**, 1592 (1949)
4. E.M. Lifshitz, L.P. Pitaevskii, V.B. Berestetskii, Quantum Electrodynamics (Butterworth-Heinemann, Oxford, 1971), Vol. 4
5. J.W. van Holten, Relativistic Time Dilation in an External Field (NIKHEF-H/91-05, 1991)
6. G. Barton, Proc. R. Soc. London Ser. A **320**, 251 (1970)
7. ALEPH, DELPHI, L3 and OPAL Collaborations, G. Abbiendi et al., Phys. Lett. B **565**, 61 (2003), http://lephiggs.web.cern.ch/LEPHIGGS/www/
8. A. Freitas, M. Awramik, M. Czakon, http://xxx.lanl.gov/abs/hep-ph/0507159
9. LEP Electroweak Working Group and LEP Collaborations, http://lepewwg.web.cern.ch/LEPEWWG/
10. G. Castellani, S. Reucroft, Y.N. Srivastava, J. Swain, A. Widom, Final State Interactions and the Effects of Potentials on Particle Reactions, http://xxx.lanl.gov/abs/hep-ph/0509089
11. ALEPH Collaboration, R. Barate et al., Eur. Phys. J. C **14**, 1 (2000)
12. DELPHI Collaboration, P. Abreu et al., Eur. Phys. J. C **16**, 371 (2000)
13. L3 Collaboration, M. Acciarri et al., Eur. Phys. J. C **16**, 1 (2000)
14. OPAL Collaboration, G. Abbiendi et al., Eur. Phys. J. C **19**, 587 (2001)
15. Particle Data Group, S. Eidelman et al., Phys. Lett. B **592**, 1 (2004), http://pdg.lbl.gov
16. ALEPH Collaboration, H. Li et al., ALEPH-2001-006 (2001)
17. ALEPH Collaboration, R. Barate et al., Phys. Lett. B **469**, 287 (1999)
18. DELPHI Collaboration, J. Abdallah et al., Eur. Phys. J. C **30**, 447 (2003)
19. L3 Collaboration, P. Achard et al., Phys. Lett. B **572**, 133 (2003)
20. L3 Collaboration, M. Acciarri et al., Phys. Lett. B **497**, 23 (2001)
21. OPAL Collaboration, G. Abbiendi et al., CERN-EP-2003-049, Eur. Phys. J. C **32**, 303 (2003)
22. OPAL Collaboration, G. Abbiendi et al., Phys. Lett. B **476**, 256 (2000)
23. ALEPH Collaboration, R. Barate et al., Eur. Phys. J. C **17**, 241 (2000)

24. DELPHI Collaboration, P. Abreu et al., Phys. Lett. B **511**, 159 (2001)
25. L3 Collaboration, M. Acciarri et al., Phys. Lett. B **454**, 386 (1999)
26. OPAL Collaboration, G. Abbiendi et al., Phys. Lett. B **507**, 29 (2001)
27. CDF Collaboration, T. Affolder et al., Phys. Rev. D **64**, 052 001 (2001)
28. D∅ Collaboration, V.M. Abazov et al., Phys. Rev. D **66**, 012 001 (2002)
29. NuTeV Collaboration, G.P. Zeller et al., Phys. Rev. Lett. **88**, 091 802 (2002)
30. NuTeV Collaboration, G.P. Zeller et al., Phys. Rev. Lett. **90**, 239 902 (2003)
31. http://www-cdf.fnal.gov/physics/new/top/top.html
32. http://www-d0.fnal.gov/Run2Physics/WWW/
33. The CDF Collaboration, the D∅ Collaboration, and the Tevatron Electroweak Working Group, Combination of CDF and D∅ Results on the Top-Quark Mass, July 2005, http://lanl.arxiv.org/abs/hep-ex/0507091
34. http://tevewwg.fnal.gov/top/
35. L. Smolin, The case for background independence, http://xxx.lanl.gov/abs/hep-th/0507235