# *Combination of tevatron searches for the standard model Higgs Boson for observing antiferromagnetism and superfluidity*



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# Combination of Tevatron Searches for the Standard Model Higgs Boson in the $W^+W^-$ Decay Mode

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We combine searches by the CDF and D0 Collaborations for a Higgs boson decaying to $W^+W^-$. The data correspond to an integrated total luminosity of 4.8 (CDF) and 5.4 (D0) fb$^{-1}$ of $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV at the Fermilab Tevatron collider. No excess is observed above background expectation, and resulting limits on Higgs boson production exclude a standard model Higgs boson in the mass range 162–166 GeV at the 95% C.L.

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Finding the last unobserved fundamental particle in the standard model (SM), the Higgs boson, is a major goal of particle physics, and the search for its existence is a central component of Fermilab's Tevatron program. Direct searches at the CERN LEP collider have set a limit on the Higgs boson mass of $m_H > 114.4$ GeV at the 95% C.L. [1]. Combining this limit with precision electroweak measurements constrains the mass of the SM Higgs boson to be less than 186 GeV at the 95% C.L. [2]. The favored mass range therefore places the SM Higgs boson within the reach of the experiments at the Fermilab Tevatron collider.

In this Letter, we combine searches for Higgs bosons ($H$) decaying to $W^+W^-$ performed by the CDF and D0 Collaborations [3,4]. These searches are particularly sensitive to a Higgs boson with mass $130 < m_H < 200$ GeV. The data analyzed correspond to integrated luminosities of 4.8 fb$^{-1}$ and 5.4 fb$^{-1}$ collected with the CDF and D0 detectors, respectively. We use all significant production modes, namely, gluon-gluon fusion ($gg \to H$), associated production ($q\bar{q} \to WH$ or $ZH$), and vector boson fusion ($q\bar{q} \to q\bar{q}H$, where the quarks radiate weak gauge bosons that fuse to form the $H$, and is referred to as VBF).

The event selections used in the CDF and D0 analyses are similar. Both collaborations select events with large missing transverse energy and two oppositely charged, isolated leptons, targeting the $H \to W^+W^-$ signal in which both $W$ bosons decay leptonically. The D0 selection classifies events in three channels, $e^+e^-$, $e^\pm\mu^\mp$, and $\mu^+\mu^-$. The CDF selection separates opposite-sign dilepton candidate events into five nonoverlapping channels, classifying events by their jet multiplicity (0, 1, or $\geq$2); the 0- and 1-jet channels are further divided depending on whether one or both leptons are in the central part of the detector. In addition, CDF searches for Higgs boson events containing same-sign lepton pairs, mainly produced in $WH$ and $ZH$ associated production.

The presence of neutrinos in the final state prevents full reconstruction of the Higgs boson mass. Other variables are used to search for a signal in the presence of appreciable background. For example, the azimuthal angle between the leptons in signal events is smaller on average than that in background events due to the scalar nature of the Higgs boson and the parity violation in $W^{\pm}$ decays. The missing transverse energy is larger, and the total transverse energy of the jets is smaller, in signal events than in background events. The final discriminants are binned neural-network outputs based on several kinematic input variables [3,4]. A dedicated network is trained for each Higgs boson mass tested. For CDF, the inputs include likelihoods constructed from matrix-element probabilities. Compared with earlier Tevatron $H \to W^+W^-$ analyses, the new analyses use larger data samples, include all significant signal production mechanisms, and have undergone additional improvements in search sensitivity.

The Higgs boson signals are simulated with PYTHIA [5], using CTEQ5L [6] (CDF) and CTEQ6L1 [7] (D0) parton distribution functions (PDF) at leading order (LO). We normalize our predictions for the Higgs boson signals to the most recent higher-order perturbative QCD calculations available. References [8,9] and references therein provide the steps used to calculate the $gg \to H$ cross section. The MSTW 2008 next-to-next-to-leading order (NNLO) PDF set [10] is used to predict the $gg \to H$ production cross section. The calculations of associated production and VBF cross sections are described in Refs. [11–13]. The branching fractions for the Higgs boson decays are obtained from HDECAY [14]. After all selections, the total number of expected Higgs boson events is approximately 30 per experiment for $m_H = 165$ GeV, which corresponds to the region of greatest sensitivity.

Both experiments determine the multijet background by studying control samples, which are then extrapolated into the signal regions. For CDF, backgrounds from SM $WW$, $WZ$, $ZZ$, $W\gamma$, Drell-Yan, and $t\bar{t}$ production are generated using the PYTHIA, MC@NLO [15], and the UB/EB [16] programs. Backgrounds from $W$ + jets processes, including (for CDF) semileptonic diboson events, single top, and semileptonic $t\bar{t}$ events, are modeled using $W$ + jets data events and a measurement of the rate at which jets are misidentified as leptons. For D0, these backgrounds are generated using PYTHIA, ALPGEN [17], and COMPHEP [18], with PYTHIA providing parton showering and hadronization for all generators.

The diboson backgrounds are normalized using next-to-leading order (NLO) calculations from MCFM [19]. The $t\bar{t}$ and single top production cross sections are taken from Refs. [20,21] and Ref. [22], respectively. NNLO calculations [23] are used by both the CDF and D0 Collaborations for the Drell-Yan background, and by D0 for the inclusive $W/Z$ processes. Other backgrounds are normalized to experimental data. Both collaborations use NLO simulations and data control samples to improve the modeling of differential distributions. Systematic uncertainties on the rates of the expected signal and the expected backgrounds, as well as on the shapes of the final discriminants, are included. More details are given in Refs. [3,4].

We perform the combination twice, using Bayesian and modified frequentist approaches in turn. We check the consistency of the results to verify that the final result does not depend on the details of the statistical formulation. Both combinations test signal mass hypotheses in 5 GeV steps for values of $m_H$ between 130 and 200 GeV, i.e., the mass range in which $H \to W^+W^-$ is the dominant decay mode. These two combinations give similar results (the limits agree within 5%). Both methods use the distributions of the final discriminants, and not just the total event counts passing selection requirements.

Both statistical procedures form, for a given Higgs boson mass, a combined likelihood [including priors on systematic uncertainties, $\pi(\vec{\theta})$] based on the product of likelihoods for the individual channels, each of which in turn is a product over histogram bins:

$$\mathcal{L}(R, \vec{s}, \vec{b}|\vec{n}, \vec{\theta})\pi(\vec{\theta}) = \prod_{i=1}^{N_C}\prod_{j=1}^{N_{\text{bins}}} \mu_{ij}^{n_{ij}} \frac{e^{-\mu_{ij}}}{n_{ij}!} \prod_{k=1}^{n_{\text{sys}}} e^{-\theta_k^2/2} \quad (1)$$

where the first product is over the number of channels ($N_C$), and the second product is over histogram bins containing $n_{ij}$ events, binned in ranges of the final neural-network discriminants used for the individual analyses. The predictions for the bin contents are $\mu_{ij} = R \times s_{ij}(\vec{\theta}) + b_{ij}(\vec{\theta})$ for channel $i$ and histogram bin $j$, where $s_{ij}$ and $b_{ij}$ represent the expected SM signal and background in the bin, and $R$ is a scaling factor applied to the signal. By scaling all signal contributions by the same factor we make the assumption that the relative contributions of the different processes at each $m_H$ are as given by the SM. Systematic uncertainties are parameterized by the dependence of $s_{ij}$ and $b_{ij}$ on $\vec{\theta}$. Each of the $n_{\text{sys}}$ components of $\vec{\theta}$, $\theta_k$, corresponds to a single independent source of systematic uncertainty scaled by its standard deviation, and each parameter may have an impact on several sources of signal and background in different channels, thus accounting for correlations.

In the Bayesian method we assume a uniform prior in the signal yield. Gaussian priors are assumed for the $\theta_k$, truncated so that no prediction is negative. The posterior density function is then integrated over the $\theta_k$ (including correlations) and a 95% C.L. upper limit on $R$, $R_{\text{lim}}$, satisfies

$$\frac{\int_0^{R_{\text{lim}}} \int \mathcal{L}(R, \vec{s}, \vec{b}|\vec{n}, \vec{\theta})\pi(\vec{\theta}) d\vec{\theta} dR}{\int_0^{\infty} \int \mathcal{L}(R, \vec{s}, \vec{b}|\vec{n}, \vec{\theta})\pi(\vec{\theta}) d\vec{\theta} dR} = 0.95. \quad (2)$$

The modified frequentist technique uses the statistical variable $CL_s$, defined in Ref. [24], to test hypotheses which correspond to the presence or absence of Higgs boson signals. The test statistic is the log-likelihood ratio LLR $= -2\ln\frac{p(\mathrm{data}|s+b)}{p(\mathrm{data}|b)}$, where $p(\mathrm{data}|s+b)$ and $p(\mathrm{data}|b)$ are the probabilities that the data are drawn from the $s+b$ and $b$-only hypotheses, respectively. The probabilities $p$ are computed using the best-fit values of the parameters $\theta_k$, separately for each of the two hypotheses [25]. The use of these fits extends the procedure used at LEP [24], improving the sensitivity when the expected signals are small and the uncertainties on the backgrounds are large. Two $p$-values are computed: $CL_b = p(\mathrm{LLR} \geq \mathrm{LLR_{obs}}|b)$ and $CL_{s+b} = p(\mathrm{LLR} \geq \mathrm{LLR_{obs}}|s+b)$, where $\mathrm{LLR_{obs}}$ is the value of the test statistic computed for the data. The ratio $CL_s = CL_{s+b}/CL_b$ is used to define confidence intervals and is chosen to reduce the potential for excluding a signal for which there is insufficient sensitivity. If $CL_s < 0.05$ for a particular choice of $s+b$, that hypothesis is excluded at the 95% C.L. Systematic uncertainties are included by fluctuating the predictions for $s_{ij}$ and $b_{ij}$ when generating the pseudoexperiments used to compute $CL_{s+b}$ and $CL_b$.

Though many sources of systematic uncertainty differ between the experiments and analyses, all appropriate correlations are taken into account in the combined limits. The dominant systematic uncertainties arise from cross section calculations for the signals and the backgrounds; these are correlated between the experiments. Variations of the parton distribution functions and the renormalization and factorization scales give rise to uncertainties of 11% for the gluon-gluon fusion process [26], 5% for associated $WH$ and $ZH$ production [11,12], and 10% for VBF [11,13]. CDF, which uses analyses separated in jet multiplicity bins, applies a channel (jet bin) dependent uncertainty of 7% to 70% and a gluon PDF uncertainty of 8% on $gg \to H$, following the treatment discussed in Ref. [26]. For the gluon-gluon fusion signal process, we study the effects on the acceptance and the kinematics of scale variations, gluon PDF variations, and the differences between next-to-next-to-leading log calculations and the generators used for the central predictions, using the FEHIP and HNNLO programs [8,27]. We find additional uncertainties of 5% to 10%. The primary background, $W^+W^-$ production, has a cross section uncertainty of 7% and a similar study of the acceptance and kinematics finds additional uncertainties of approximately 1% to 5%. The systematic uncertainties on $WZ$, $ZZ$, $t\bar{t}$, single top production, and Drell-Yan production range from 7% to 10%. The uncertainties on the multijet background are uncorrelated between the experiments and range from 2% to 15%. The uncertainties on the yields of $W$ + jets and $W\gamma$(+jets) range from 7% to 30%, but these have small effects on the results because the rates of these backgrounds are low. Because the methods of estimating the $W$ + jets and $W\gamma$(+jets) backgrounds differ between CDF and D0, we assume there is no correlation between these rates. The uncertainties on the lepton identification and the trigger efficiencies are uncorrelated between the experiments and range from 2% to 6%. The uncertainty on the integrated luminosity of 6% is taken to be correlated between the signal and the Monte Carlo–based background predictions, and partially correlated between the experiments, via the 4% uncertainty on the inelastic $p\bar{p}$ cross section [28]. Additional details related to the treatment of systematic uncertainties are given in

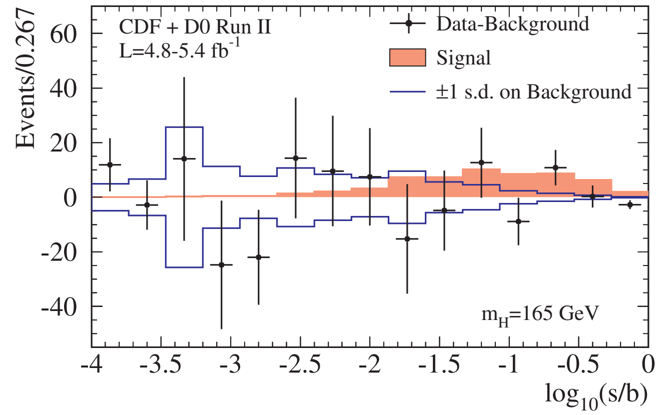


FIG. 1 (color online). Background-subtracted data distributions for the discriminant histograms, summed for bins with similar $s/b$, for the $m_H = 165$ GeV combined search. The background has been fit to the data under the $b$-only hypothesis, and the uncertainty on the background is the post-fit systematic uncertainty. The signal, which is normalized to the SM expectation, is shown with a filled histogram. The uncertainties shown on the background-subtracted data points are the square roots of the post-fit background predictions in each bin, representing the expected statistical uncertainty on the data.

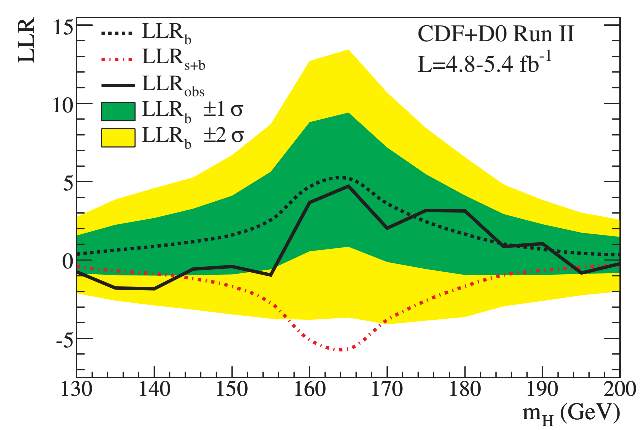


FIG. 2 (color online). Distributions of LLR as functions of the Higgs boson mass. We display the median values of the LLR distribution for the $b$-only hypothesis ($\mathrm{LLR}_b$), the $s+b$ hypothesis ($\mathrm{LLR}_{s+b}$), and for the data ($\mathrm{LLR_{obs}}$). The shaded bands indicate the 68% and 95% probability regions in which the LLR is expected to fluctuate, in the absence of signal.

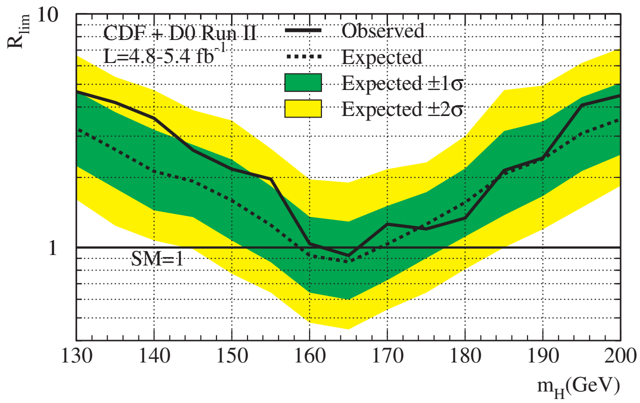


FIG. 3 (color online). Observed and expected (median, for the background-only hypothesis) 95% C.L. upper limits on SM Higgs boson production. The shaded bands indicate the 68% and 95% probability regions in which $R_{\rm lim}$ is expected to fluctuate, in the absence of signal. The limits displayed in this figure are obtained with the Bayesian calculation.

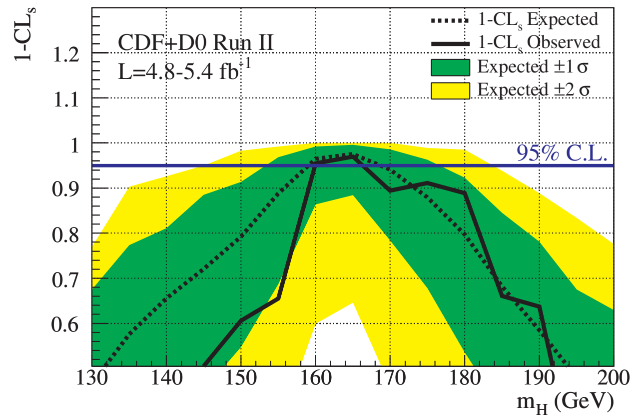


FIG. 4 (color online). Distribution of 1-CL$_s$ as a function of the Higgs boson mass obtained with the CL$_s$ method. The shaded bands indicate the 68% and 95% probability regions in which the LLR is expected to fluctuate, in the absence of signal.

Refs. [3,4]. As bin by bin uncertainties arising from the statistical uncertainty in the Monte Carlo (and in some cases data) samples were shown to affect the observed and expected limits by less than 1%, they are neglected.

To better visualize the impact of the data events, we combine the histograms of the final discriminants, adding the contents of bins with similar $s/b$ ratios, so as not to dilute the impact of highly-sensitive bins with those with less discriminating power. Figure 1 shows the signal expectation and the data with the background subtracted, as a function of the $s/b$ ratio of the collected bins. The background model has been fit to the data, and the uncertainties on the background are those after the systematic uncertainties have been constrained by the fit. No excess of candidate events in the highest $s/b$ bins relative to the background expectation is observed.

Before extracting the combined limits, we study the LLR distributions for the $s + b$ and $b$-only hypotheses, shown in Fig. 2 as functions of $m_H$. The separation between the median LLR$_b$ and LLR$_{s+b}$ divided by the widths is a measure of the discriminating power of the search. The value of LLR$_{\rm obs}$ relative to the expected $s + b$ and $b$-only distributions indicates whether the observed data are more consistent with the presence of signal, or not. No significant excess of data above the background expectation is seen for any value of $m_H$. Because the same data events are used to construct the observed LLR at each $m_H$ tested, the LLR values are highly correlated from one $m_H$ to the next. This also applies to Figs. 3 and 4 described below.

We extract limits on SM Higgs boson production in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV in the $m_H = 130$–200 GeV mass range. We present our results in terms of $R_{\rm lim}$, the ratio of the limits obtained to the rate predicted by the SM, as a function of the Higgs boson mass. We assume the production fractions for $WH$, $ZH$, $gg \to H$, and VBF, and the Higgs boson decay branching fractions, are those predicted by the SM. A value of $R_{\rm lim}$ less than or equal to one indicates a Higgs boson mass that is excluded at the 95% C.L.

The ratios of the expected and observed limits to the SM cross section are shown in Fig. 3 as a function of $m_H$. The observed and median expected ratios are listed in Table I, with observed (expected) values for the Bayesian method of 1.04 (0.92) at $m_H = 160$ GeV, 0.93 (0.87) at $m_H = 165$ GeV, and 1.26 (1.04) at $m_H = 170$ GeV. We use piecewise linear interpolations to display the combination results in Figs. 2–4, and to quote the observed and expected excluded mass ranges. We exclude the SM Higgs boson in the mass range 162 to 166 GeV. The Bayesian calculation,

TABLE I. Ratios, $R_{\rm lim}$, of the median expected and observed 95% C.L. limits to the SM cross section for the combination of CDF and D0 analyses as a function of the Higgs boson mass in GeV, obtained with the Bayesian (upper) and the CL$_s$ (lower) methods.

| Bayesian | 130 | 135 | 140 | 145 | 150 | 155 | 160 | 165 | 170 | 175 | 180 | 185 | 190 | 195 | 200 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Expected | 3.24 | 2.63 | 2.12 | 1.92 | 1.59 | 1.25 | 0.92 | 0.87 | 1.04 | 1.26 | 1.56 | 2.07 | 2.40 | 3.09 | 3.55 |
| Observed | 4.65 | 4.18 | 3.58 | 2.61 | 2.17 | 1.96 | 1.04 | 0.93 | 1.26 | 1.20 | 1.34 | 2.14 | 2.42 | 4.07 | 4.47 |
| CL$_s$ | 130 | 135 | 140 | 145 | 150 | 155 | 160 | 165 | 170 | 175 | 180 | 185 | 190 | 195 | 200 |
| Expected | 3.26 | 2.52 | 2.18 | 1.87 | 1.53 | 1.24 | 0.89 | 0.84 | 1.06 | 1.28 | 1.56 | 2.07 | 2.46 | 3.17 | 3.62 |
| Observed | 4.49 | 4.06 | 3.45 | 2.49 | 2.12 | 1.84 | 0.98 | 0.89 | 1.21 | 1.18 | 1.31 | 2.15 | 2.36 | 4.10 | 4.35 |

chosen *a priori*, was used for this exclusion. The corresponding expected exclusion, from 159 to 169 GeV, encompasses the observed exclusion. The $CL_s$ calculation yields similar results, as shown in Fig. 4. The 1-$CL_s$ distribution, which can be directly interpreted as the level of exclusion of our search, is displayed as a function of the Higgs boson mass. For instance, our expected limit shows that in the absence of signal the median 1-$CL_s$ value with which we expect to exclude a SM Higgs boson of mass 165 GeV is 97%.

In summary, we present the first combined Tevatron search for the SM Higgs boson using the $H \to W^+W^-$ decay mode. No significant excess of candidates is found above the background expectation for $130 < m_H < 200$ GeV. We exclude the mass range from 162 to 166 GeV at the 95% C.L. This is the first direct constraint on the mass of the Higgs boson beyond that obtained at LEP.

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[1] The ALEPH, DELPHI, L3, OPAL Collaborations, and The LEP Working Group for Higgs Boson Searches, Phys. Lett. B **565**, 61 (2003).

[2] ALEPH, CDF, D0, DELPHI, L3, OPAL, SLD Collaborations, The LEP Electroweak Working Group, The Tevatron Electroweak Working Group, and The SLD Electroweak and Heavy Flavour Groups, arXiv:0911.2604.

[3] T. Aaltonen *et al.* (CDF Collaboration), this issue, Phys. Rev. Lett. **104**, 061803 (2010).

[4] V. Abazov *et al.* (D0 Collaboration), this issue, Phys. Rev. Lett. **104**, 061804 (2010).

[5] T. Sjöstrand, S. Mrenna, and P. Skands, J. High Energy Phys. 05 (2006) 026. CDF uses PYTHIA version 6.216 to generate the Higgs boson signals, and D0 uses version 6.323. Both collaborations use ''Tune A'' settings.

[6] H. L. Lai *et al.*, Eur. Phys. J. C **12**, 375 (2000).

[7] J. Pumplin *et al.*, J. High Energy Phys. 07 (2002) 012.

[8] C. Anastasiou, R. Boughezal, and F. Petriello, J. High Energy Phys. 04 (2009) 003.

[9] D. de Florian and M. Grazzini, Phys. Lett. B **674**, 291 (2009).

[10] A. D. Martin, W. J. Stirling, R. S. Thorne, and G. Watt, Eur. Phys. J. C **63**, 189 (2009).

[11] K. A. Assamagan *et al.*, arXiv:hep-ph/0406152.

[12] O. Brein, A. Djouadi, and R. Harlander, Phys. Lett. B **579**, 149 (2004); M. L. Ciccolini, S. Dittmaier, and M. Krämer, Phys. Rev. D **68**, 073003 (2003).

[13] E. Berger and J. Campbell, Phys. Rev. D **70**, 073011 (2004).

[14] A. Djouadi, J. Kalinowski, and M. Spira, Comput. Phys. Commun. **108**, 56 (1998).

[15] S. Frixione and B. R. Webber, J. High Energy Phys. 06 (2002) 029.

[16] U. Baur and E. L. Berger, Phys. Rev. D **47**, 4889 (1993).

[17] M. L. Mangano, M. Moretti, F. Piccinini, R. Pittau, and A. D. Polosa, J. High Energy Phys. 07 (2003) 001.

[18] A. Pukhov *et al.*, arXiv:hep-ph/9908288v2.

[19] J. M. Campbell and R. K. Ellis, Phys. Rev. D **60**, 113006 (1999).

[20] S. Moch and P. Uwer, Nucl. Phys. B, Proc. Suppl. **183**, 75 (2008).

[21] A. D. Martin *et al.*, Phys. Lett. B **652**, 292 (2007).

[22] N. Kidonakis, Phys. Rev. D **74**, 114012 (2006).

[23] R. Hamberg, W. L. van Neerven, and T. Matsuura, Nucl. Phys. **359**, 343 (1991); **644**, 403(E) (2002).

[24] T. Junk, Nucl. Instrum. Methods Phys. Res., Sect. A **434**, 435 (1999); A. L. Read, J. Phys. G **28**, 2693 (2002).

[25] W. Fisher, Fermilab Report No. FERMILAB-TM-2386-E, 2006.

[26] C. Anastasiou *et al.*, J. High Energy Phys. 08 (2009) 99.

[27] S. Catani and M. Grazzini, arXiv:0802.1410.

[28] S. Klimenko, J. Konigsberg, and T. M. Liss, Fermilab Report No. FERMILAB-FN-0741, 2003.