CP-violating MSSM Higgs at Tevatron and LHC

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Abstract.
We analyze the prospect for observing the intermediate neutral Higgs boson ($h_2$) in its decay to two lighter Higgs bosons ($h_1$) at the presently operating hadron colliders in the framework of the CP violating MSSM using the PYTHIA event generator. We consider the lepton+ 4-jets+ $E_T$ channel from associate $W h_2$ production, with $W h_2 \rightarrow W h_1 h_1 \rightarrow \nu b\bar{b}bb$. We require two or three tagged $b$-jets. We explicitly consider all relevant Standard Model backgrounds, treating $c$-jets separately from light flavor and gluon jets and allowing for mistagging. We find that it is very hard to observe this signature at the Tevatron, even with 20 fb\textsuperscript{-1} of data, in the LEP–allowed region of parameter space due to the small signal efficiency. At the LHC, a priori huge SM backgrounds can be suppressed by applying judiciously chosen kinematical selections. After all cuts, we are left with a signal cross section of around 0.5 fb, and a signal to background ratio between 1.2 and 2.9. According to our analysis this Higgs signal should be viable at the LHC in the vicinity of present LEP exclusion once 20 to 50 fb\textsuperscript{-1} of data have been accumulated at $\sqrt{s} = 14$ TeV.

1. Introduction
The Minimal Supersymmetric Standard Model (MSSM) \cite{1} requires two Higgs doublets, leading to a total of five physical Higgs bosons. At the tree level, these can be classified as two neutral CP–even bosons ($\phi_1$ and $\phi_2$), one neutral CP–odd boson ($a$) and two charged bosons. In the presence of CP violation, the three neutral Higgs bosons can mix radiatively \cite{2,3}. The mass eigenstates $h_1$, $h_2$ and $h_3$ with $m_{h_1} < m_{h_2} < m_{h_3}$ can then be obtained from the interaction eigenstates $\phi_1$, $\phi_2$ and $a$ with the help of the orthogonal matrix $O_{ai}$, $(\phi_1,\phi_2,a)^T = O_{ai}(h_1,h_2,h_3)^T$, which diagonalizes the Higgs boson mass matrix. $O$ depends on various parameters of the SUSY Lagrangian.

Due to this mixing, the Higgs mass eigenstates are no longer CP eigenstates. Moreover, the masses of the Higgs bosons, their couplings to SM and MSSM particles, and their decays are significantly modified \cite{3}. For example, the Higgs boson couplings to pairs of gauge bosons are scaled by $g_{hVV}$ relative to the SM. These couplings can be expressed as $g_{hVV} = \cos \beta O_{\phi_1 i} + \sin \beta O_{\phi_2 i}$, where $\tan \beta$ is the ratio of Higgs vacuum expectation values (VEVs). The magnitude of $g_{hWW}$ is directly related to the production process studied in this paper.

In the absence of mixing between neutral CP–even and CP–odd states the LEP experiments were able to derive absolute lower bounds of about 90 GeV on the masses of both the lighter...
CP–even Higgs and the CP–odd boson \[4\]. However, in the presence of CP violation, the LEP experiment were not able to exclude certain scenarios with very light \(h_1\). In this “LEP hole” \(h_1\) is dominantly a CP–odd state with almost vanishing coupling to the Z boson. One then has to search for \(Zh_2\) or \(h_1 h_2\) production. In part of the LEP hole, these cross sections are suppressed by the rather large \(h_2\) mass. Moreover, \(h_2 \to h_1 h_1\) decays lead to quite complicated final states, which often yield low efficiencies after cuts. One LEP–allowed region has \(m_{h_2}\) less than 10 GeV, so that \(h_1 \to \tau^+ \tau^-\) is dominant; in the other, \(m_{h_1} \sim 30 - 50\) GeV so that \(h_1 \to b\bar{b}\) is dominant. \(m_{h_2}\) lies between slightly below 90 and slightly above 130 GeV. Scenarios with even lighter \(h_2\) are excluded by decay–independent searches for \(Zh_2\) production \[4\]. If \(m_{h_2}\) is much above 130 GeV, the CP–odd component of \(h_1\) becomes subdominant, so that the cross section for \(Zh_1\) production becomes too large. Finally, the LEP hole occurs for \(\tan \beta\) in between 3 and 10 \[4\]. We analyze the prospect for observing a signal for the production of neutral Higgs bosons in the second of these LEP allowed regions.

2. Numerical analysis

In our analysis we took five different benchmark points, denoted by S1 through S5 \([m_{h_2} = 130-90\) GeV with \(m_{h_1} = 30\) GeV and two CPX\(_{0.5}\) scenario \([CPX-1(2)\) where \(m_{h_2} = 102 \) (103) GeV with \(m_{h_1} = 36\) (45) GeV, which can be realized for \(M_{\tilde{t}} = 131.8\) GeV with \(\tan \beta = 4.02\) (4.39)\) of the MSSM \[5\]. We calculated the spectrum and the couplings for these two benchmark points using \(CPsuperH\) \[3\]. In our simulation we used the \(PYTHIA\) v6.408 \[6\] event generator with the \(SLHA\) \[7\] interfacing option. We used \(MadGraph/MadEvent\) v4.2.8 \[8\] for generating parton level SM backgrounds which were fed to \(PYTHIA\) for showering. We set the renormalization and factorization scale to \(Q = \sqrt{s}\) and used \(CTEQ5L\) for the parton distribution functions (PDF).

The signal arises from \(p\bar{p} \to Wh_2 \to \ell \nu_\ell h_1 h_1 \to \ell \nu_\ell b \bar{b}\), leading to \(\ell jjjj \ell T\) events, where \(\ell = e\) or \(\mu\). The effective cross section for this signal topology can be expressed as,

\[
\sigma_{\text{signal}}^{\text{tot}} = \sigma_{\text{SM}}(pp/\bar{p}p \to Wh_2) \times g_{h_2WW}^2 \times Br(h_2 \to h_1 h_1) \times Br(h_1 \to b\bar{b})^2 \times 2 Br(W \to \ell\nu_\ell\ell) ,
\]

where \(g_{h_2WW}\) is the \(h_2WW\) coupling in units of the corresponding SM value, \(W\) stands for \(W^\pm\) and the factor 2 is for \(\ell = e\) and \(\mu\). This process has recently been studied in refs.\[9, 10\], using parton–level analyses with quite promising results. We instead performed a full hadron–level analysis, including initial and final state showering as well as the underlying event. We take \(g_{h_2WW}^2 \times Br(h_2 \to h_1 h_1) \times Br(h_1 \to b\bar{b})^2 = 0.50\).

We simulate our signal and backgrounds at Tevatron Run–II with \(\sqrt{s} = 1.96\) TeV. We have used the toy calorimeter simulation (\(PYCELL\)) provided in \(PYTHIA\) with the following criteria: calorimeter coverage is \(|\eta| < 3.64\); the segmentation is given by \(\Delta \eta \times \Delta \phi = 0.16 \times 0.098\) which resembles the CDF detector \[11\]; Gaussian smearing of the total energy of jets and leptons; a cone algorithm with \(\Delta R(j, j) = \sqrt{\Delta \eta^2 + \Delta \phi^2} = 0.4\) has been used for jet finding; \(E_{T,\text{min}}^{\text{cell}} \geq 1.5\) GeV is considered to be a potential candidate for jet initiator; minimum summed \(E_{T,\text{min}}^{\text{jet}} \geq 10.0\) GeV is accepted as a jet and the jets are ordered in \(E_T\); leptons (\(\ell = e\), \(\mu\)) are selected with \(E_{T,\text{cut}} \geq 15.0\) GeV and \(|\eta_\ell| \leq 2.0\) and no jet should match with a hard lepton in the event. We reconstructed the missing energy (\(E_{T,\text{miss}}\)) from all observed particles.

The tagging of \(b\)–jets plays a crucial role in our analysis. A jet with \(|\eta_\ell| \leq 1.2\) and \(E_{T,\text{cut}} \geq 15\) GeV “matched” with a \(b\)–flavored hadron (\(B\)–hadron), i.e. with \(\Delta R(j, B - \text{hadron}) < 0.2\), is considered to be “taggable”. We assume that such jets are actually tagged with with probability \(\epsilon_b = 0.50\) \[12\]. We find that our tagging algorithm agrees well with the \(t\bar{t}\) analysis of CDF \[13\]. We also modeled mistagging of non–\(b\) jets as \(b\)–jets, treating \(c\)–jets differently from those due to gluons or light quarks with \(\epsilon_c = 0.10\) and \(\epsilon_{u,d,s,g} = 0.01\).

The cross-sections for the signal benchmarks lie in between 0.045 – 0.16 pb while the total background is approximately 455 pb. We have displayed the raw number of events for signal
Figure 1. The four-jet invariant mass $m_{4j}$ distribution after all cuts for signal scenarios S1, S3 and S5 and for the total background (ToB), requiring triple $b$-tag following the last column of Table 1 at Tevatron.

Figure 2. The four-jet invariant mass $m_{4j}$ distribution after all cuts for signal scenarios S1, S3 and S5 and for the total background (ToB), requiring triple $b$-tag following the last column of Table 1 at LHC.

and backgrounds in the first column in Table 1. The second column is the number of events after applying the following basic acceptance cuts: $N_{\text{jet}} \geq 4$, $E_T^{i=1-4} > 10$ GeV, $|\eta^i|<3.0$; $N_{\text{lepton}} \geq 1$, $E_T > 15$ GeV, $|\eta|<2.0$ and $E_T \geq 15$ GeV. Not surprisingly, $t\bar{t}$ is the main source of background at this stage. We found that the suppressions by applying $N_{b-\text{tag}} \geq 2$ are almost the same for signal and $t\bar{t}$. The signal contains more $b$ quarks, but the $t\bar{t}$ background has much harder $b$ jets, leading to larger tagging probabilities. However, this background can contain a third $b$ jet only due to showering. Hence requiring $N_{b-\text{tag}} \geq 3$ greatly reduces the background and increases the signal-to-background ratio. Unfortunately the small triple $b$-tagging probability, which lies between 1.3 and 3.6% depending on $m_{h_2}$, also reduces the signal rate.

We have also looked for invariant mass peaks to isolate the signal on top of a sizable background. In addition to the basic acceptance cuts (defined above) we demand that the signal contains exactly (rather than at least) four jets. This reduces combinatorial backgrounds for Higgs mass reconstructions. Finally, we pick the jet pairing $(ij)(kl)$ (with $i, j, k, l \in \{1, 2, 3, 4\}$) that minimizes the difference $m_{ij} - m_{kl}$ of di-jet invariant masses; in the absence of showering and for perfect energy resolution, the signal would have $m_{ij} = m_{kl} = m_{h_1}$. We then demand that both $m_{ij}$ and $m_{kl}$ lie between 10 and 60 GeV, where the lower bound comes from the requirement that $h_1 \rightarrow bb$ decays should be allowed, and the upper bound from the requirement that $h_2 \rightarrow h_1h_1$ decays should be open. We next require the four-jet invariant mass to lie between 60 and 140 GeV; this covers the entire “LEP hole” in the MSSM Higgs parameter space. Table 1 shows that after these cuts, the signal actually exceeds the total background.

The results of the column labeled $E3$ in Table 1 have been obtained by including all events that pass the other cuts (not related to tagging) and have at least three taggable jets, assigning each event a weight given by its (mis)tagging probability. This greatly increases the statistics. We checked that this gives results that are consistent with the event rejection technique whenever the latter has good statistics; this is the case if at most one $b$-tag results from mistagging.

The distribution of $m_{4j}$ is shown in Fig. 1 for signal scenarios S1, S3 and S5 as well as for the
Table 1. Process column shows the signal benchmarks and the SM backgrounds, where \( j \) stands for \( u, d, s, g \) and \( - \) for background process 7 and 8. RawEvt is stands for the number of events produced in the experiments (for backgrounds we applied basic preselections in the generator level: \( p_T^{j,b} \geq 5 \) GeV, \( |p_T^{j,b}|<5.0 \) and \( \Delta R(jj,bb,bj) \geq 0.3 \). \( N_{acc} \) is the number after the basic selection cuts, whereas \( N_{3b} \) is with at least three jets tagged as \( b \)-jets, allowing for mistagging. Eff3 is the number of events passing the selection cuts that contain exactly four jets and at least 3\( b \)-tagged jets; the numbers in parentheses represent the number of events with the inclusion of \( m_{pair} \) and \( m_{4j} \) cuts. Finally, ToB is the total number of background events.

| Process | Tevatron with 4fb \(^{-1}\) | LHC with 10fb \(^{-1}\) |
|---------|-----------------------------|-----------------------------|
|         | RawEvt | \( N_{acc} \) | \( N_{3b} \) | Eff3 (+h1) | RawEvt | \( N_{acc} \) | \( N_{3b} \) | Eff3(+h1) |
| S1      | 38.11  | 11.09 | 0.77 | 0.49 (0.40) | 1157  | 352.5 | 33.48 | 13.96(6.85) |
| S2      | 51.59  | 13.85 | 0.83 | 0.51 (0.44) | 1486  | 418.3 | 36.84 | 15.36(7.76) |
| S3      | 68.91  | 16.58 | 0.83 | 0.54 (0.47) | 1962  | 506.5 | 39.81 | 17.03(8.91) |
| S4      | 94.76  | 19.88 | 0.87 | 0.54 (0.46) | 2620  | 610.6 | 43.18 | 17.81(9.61) |
| S5      | 133.6  | 23.92 | 0.86 | 0.52 (0.45) | 3516  | 724.7 | 43.92 | 18.96(9.63) |
| CPX-1   | 89.89  | 20.27 | 0.82 | 0.49 (0.43) | 2509  | 597.2 | 40.07 | 17.25(9.07) |
| CPX-2   | 87.56  | 22.46 | 0.84 | 0.53 (0.47) | 2421  | 597.2 | 40.07 | 17.25(9.07) |
| \( tt \) | 6760   | 3545  | 25.62| 9.65(0.05)  | 1,690,000 | 818,800 | 7795 | 1469(5.52) |
| \( bbbW \) | 12.59  | 1.52  | 0.06 | 0.03(0.01)| 337.6 | 31.8  | 4.10 | 2.95(0.53) |
| \( bbjjW \) | 0.043  | 0.01  | 0   | 0(0) | 23.3  | 2.3   | 0.13 | 0.11(0.01) |
| \( bccW \) | 131.2  | 17.6  | 0.05 | 0.02(0.01)| 73,170 | 7539  | 77.56 | 56.50(6.79) |
| \( bccW \) | 44.51  | 5.53  | 0.03 | 0.01(0.01) | 1126  | 89.9  | 1.68 | 1.17(0.25) |
| \( bjjjW \) | 5181   | 610.2 | 0.28 | 0.15(0.06)| 535,700 | 48,830 | 17.14 | 17.89(1.93) |
| \( jjjjW \) | 384000 | 47340 | 0.24 | 0.02(0.01) | 7194  | 586.3 | 0.23 | 0.05(0.01) |
| \( t\bar{t}\bar{b} \) | 12.15  | 6.80  | 0.44 | 0.03(0.01)| 10,100 | 5700  | 751.5 | 72.82(1.28) |
| \( tt\bar{c} \) | 21.69  | 13.66 | 0.19 | 0.02(0.01)| 16,440 | 9245  | 259.8 | 31.54(0.45) |
| \( \text{ToB} \) | 396200 | 51550 | 26.91| 9.93(0.14) | 62,030,000 | 5,220,000 | 2910 | 1657(17.45) |

total background. We observe clear peaks for the signal, which are shifted downwards due to, for example, showering (by 10 to 15 GeV) from the naive expectation \( m_{4j} = m_{h_2} \) at the parton level.

By seeing the distributions of \( m_{pair} \) (average of the two optimal pairing of di-jet invariant masses) and \( m_{4j} \) (see Fig. 1) allow us define the final significance of the signal by counting events that satisfy: 0\( : m_{h_1} < m_{pair} < m_{h_1} + 5 \) GeV and 0\( : m_{h_2} < m_{4j} < m_{h_2} + 10 \) GeV. We see that requiring triple \( b \)-tags leads to very good signal to background ratio, of around 10 for \( m_{h_1} = 30 \) GeV and slightly less for heavier \( h_1 \). However, we expect less than 2 signal events after all cuts for a total integrated luminosity (\( \int \mathcal{L} dt \)) of 20 fb\(^{-1}\). We tried also to see the effect for two \( b \)-tag and found that the signal rate increase by a factor between 3.7 and 5 while the background increases by two orders of magnitude and \( S/\sqrt{B} \) is well below two.

The significance defined in this way overestimates the true statistical significance of a double peak in the \( m_{pair} \) and \( m_{4j} \) distributions somewhat, due to the “look elsewhere” effect: since \( m_{h_1} \) and \( m_{h_2} \) are not known a priori, one would need to try different combinations when looking for peaks. However, given that we use rather broad search windows, there are probably only \( \mathcal{O}(10) \) statistically independent combinations within the limits of the LEP hole. Note also that the
signal rate is still quite small. Further kinematical cuts, which might slightly increase the signal to background ratio, are therefore not likely to increase the statistical significance of the signal. We are therefore forced to conclude that the search for $W h_2 \rightarrow W h_1 h_1 \rightarrow \ell\nu bbbh$ events at the Tevatron does not seem promising, and turn instead to the LHC.

Our analysis for the LHC follows broadly similar lines as that for the Tevatron. We simulate our signal and backgrounds at the LHC with $\sqrt{s} = 14$ TeV. The PYCELL model is based on the ATLAS detector [14] with calorimeter coverage $|\eta| < 5.0$, segmentation $\Delta\eta \times \Delta\phi = 0.087 \times 0.10$. We use a Gaussian energy resolution for leptons and jets and a cone algorithm for jet finding, with $\Delta R(j,j) = 0.4$. Calorimeter cells with $E_{\text{cell}}^{\text{jet}} \geq 1.0$ GeV are considered to be a potential candidates for jet initiator. All cells with $E_{\text{cell}}^{\text{jet}} \geq 0.1$ GeV are treated as part of the would-be jet; minimum summed $E_{\text{jet}}^{\text{jet}} \geq 15.0$ GeV is accepted as a jet and the jets are ordered in $E_T$; leptons ($\ell = e, \mu$) are selected if they satisfy $E_T^{\ell} \geq 20$ GeV and $|\eta^{\ell}| \leq 2.5$. The jet–lepton isolation criterion and the missing transverse energy $E_T^\text{miss}$ are adopted similar to our Tevatron analysis.

Only jets with $|\eta_j| < 2.5$ are considered to be taggable as $b$–jets. If the jet is “matched” to a $b$–flavored hadron, with $\Delta R(j, \text{hadron}) \leq 0.2$, the tagging efficiency is taken to be 50%. If instead the jet is matched to a $c$–hadron, the (mis)tagging efficiency is taken to be 10%, whereas jets matched to a $\tau$–lepton have zero tagging probability. All other taggable jets have (mis)tagging probability of 0.25%. These efficiencies follow recent ATLAS analyses [15, 16, 17].

The cross-sections for the signal benchmarks lie between 0.5 – 1.7 pb while the total backgrounds is approximately $2.84 \cdot 10^4$ pb. We have displayed the raw number of events for signal and backgrounds (again with the same generator–level cuts as of Tevatron) in the first column in Table 1. The second column is the number of events after applying the basic acceptance cuts: $N_{\text{jet}} \geq 4, E_T^{\text{jet}} > 15$ GeV, $|\eta^{\text{jet}}| < 5.0$; $N_{\text{lepton}} \geq 1, E_T^{\ell} > 20$ GeV $|\eta^{\ell}| < 2.5$ and $E_T > 20$ GeV. They reduce the cross section by about a factor of 5 (3) for $m_{h_2} = 90$ (130) GeV.

The number of events (for $\int \mathcal{L}dt = 10$ fb$^{-1}$) passing the acceptance cuts and containing exactly four jets, at least three of which are tagged (adopting the same strategy like Tevatron), is given by the ElB3 column of Table 1. Similar to Tevatron we require both jet pair invariant masses to lie between 10 and 60 GeV and $m_{jj}$ to lie between 60 and 140 GeV. The $m_{jj}$ distribution is shown in Fig. 2. After these cuts we are left with slightly less than one signal event and slightly less than two background events per fb$^{-1}$ of data. A 5$\sigma$ signal would then require almost 100 fb$^{-1}$ of data, more than the LHC is likely to collect during “low” luminosity running.

We also checked that requiring a fourth $b$–tag reduces the signal cross section by another order of magnitude or more. The signal rate then becomes so low that one would have to wait for the high–luminosity phase of the LHC to accumulate enough events to reconstruct invariant mass peaks. We therefore stick to triple $b$–tag in our LHC analysis.

We found that the background shows a peak in the $m_{\text{pair}}$ distribution between 30 and 40 GeV, not far from the peak of the signal in the scenarios we consider. A tighter cut on $m_{\text{pair}}$ will nevertheless improve the signal–to–background ratio. Moreover, the four–jet invariant mass distribution (in Fig. 2) of the background peaks at large values, largely due to the contribution from $t\bar{t}$ production. At least for scenarios with $h_2$ masses in the lower half of the “LEP hole” region a tighter cut on $m_{jj}$ will therefore also improve the significance of the signal. We therefore applied the same “double–peak” cuts as at the Tevatron. The signal then always exceeds the background. Assuming an integrated luminosity of 60 fb$^{-1}$ at the end of “low” luminosity running, we find a final statistical significance of at least 5 standard deviations, and a signal sample of some 30 events.
3. Conclusions
We analyzed the possibility of observing neutral Higgs bosons at currently operating hadron colliders in the framework of the CP violating MSSM. We explored the $\ell jjjjE_T$ channel with double, triple and quadruple $b$ tag, focusing on the region of parameter space not excluded by LEP searches. We considered a large number of SM backgrounds and employed a full hadron–level Monte Carlo simulation using the PYTHIA event generator. We carefully implemented $b$–tagging, including mistagging of $c$–jets or light flavor or gluon jets. At the Tevatron, requiring $3b$–tag, we can only expect about one signal event per $10 \text{ fb}^{-1}$ of $\int L dt$, on a background of about 0.3 events. If we require only $2b$–tag, the signal increases by a factor of about 4, but the background increases by two orders of magnitude, making the signal unobservable. At the LHC we focussed on events with exactly four jets, cutting simultaneously on the average di–jet invariant mass and the four–jet invariant mass and demanding at least $3b$-tags. We found a signal rate above the background, and a signal significance exceeding 5 standard deviations. One might be able to increase the S:B ratio even more by requiring 4$b$–tags with softer tagging criteria (enhancing mistag rate also), possibly simultaneously relaxing the requirement on the number of jets. This could be used to confirm the existence of a signal.

We conclude that searches for $Wb\bar{b}$ production at the LHC with $W \rightarrow \ell v$ and $h_2 \rightarrow h_1 h_1 \rightarrow b\bar{b}b\bar{b}$ should be able to close that part of the “LEP hole” in parameter space where $h_1 \rightarrow b\bar{b}$ decays dominate. The details of this analysis can be found in our recent paper [18].

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References
[1] For introductions into supersymmetric extensions of the Standard Model in general, and the MSSM in particular, see e.g. M. Drees, R.M. Godbole and P. Roy, Theory and Phenomenology of Sparticles, World Scientific, Singapore (2004); H.A. Baer and X.R. Tata, Supersymmetry: from superfields to scattering events, Cambridge Press (2006).
[2] A. Pillafsis, Phys. Rev. D58 (1998) 096010; Phys. Lett. B435 (1998) 88; E. Accamando et al., arXiv:hep-ph/0608079.
[3] J.S. Lee et al., Comput. Phys. Commun. 156 (2004) 283; Comput. Phys. Commun. 180, 312 (2009).
[4] S. Schael et al. (ADLO Collab.) Eur. Phys. J. C 47 (2006) 547; OPAL Collab., G. Abbiendi et al., Eur. Phys. J. C27 (2003) 311; DELPHI Collab., J. Abdallah et al., Eur. Phys. J. C38 (2004) 1; P. Bechtle et al., Comput. Phys. Commun. 181 (2010) 138.
[5] M. Carena, J.R. Ellis, A. Pillafsis and C.E.M. Wagner, Phys. Lett. B 495 (2000) 155, hep-ph/0009212.
[6] T. Sjostrand, S. Mrenna and P. Skands, JHEP 0605, 026 (2006).
[7] P. Slatats et al., JHEP 0407, 036 (2004).
[8] F. Maltoni and T. Stelzer, JHEP 0302, 027 (2003).
[9] K. Cheung, J. Song and Q.-S. Yan, Phys. Rev. Lett. 99 (2007) 031801, hep-ph/0703149.
[10] M. Carena, T. Han, G.Y. Huang and C.E.M. Wagner, JHEP 0804, 092 (2008), arXiv:0712.2466 [hep-ph].
[11] CDF Collab., T. Aaltonen et al., Phys. Rev. Lett. 100 (2008) 091803; CDF IIb Collab., P. T. Lukens, The CDF IIb detector: Technical design report, FERMILAB-TM-2198.
[12] K. Hanagaki [D0 Collab.], FERMILAB-CONF-05-647-E; C. Neu [CDF Collab.], FERMILAB-CONF-06-162-E; T. Wright [CDF and D0 Collabs.], arXiv:0707.1712 [hep-ex]; M.T. Bowen et al., Phys. Rev. D 72, 074016 (2005).
[13] D. Acosta et al., Phys. Rev. D 71 (2005) 052003.
[14] The Atlas Collab., CERN-LHCC-99-15, ATLAS-TDR-15 (1999).
[15] G. Aad et al. [The ATLAS Collab.], arXiv:0901.0512 [hep-ex].
[16] M. Lehnacher, arXiv:0809.4896 [hep-ex].
[17] E. Alageoz et al., Particle Physics with CMS for the LHC, http://unizh.web.cern.ch/unizh/Activities/cms.htm.
[18] S. P. Das and M. Drees, to appear.