Higgs and B physics in Run II

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Abstract

In Run II at the Tevatron, the major goal of the upgraded CDF and DØ detectors is a Higgs search in the mass range of $110 - 200$ GeV. They will also contribute significantly to B physics. Among many possibilities they will be able to measure rare decays of B mesons and improve our knowledge of CP violation in B system through study of B mixing. Various aspects of Higgs and B physics in Run II are discussed here.

1 Introduction

Both of the CDF and DØ detectors, are undergoing major upgrades in Run II, which will start in March, 2001. The Tevatron will deliver approximately 2 fb^{-1} integrated luminosity to each experiment, a factor of 20 more than the Run I data samples. This will provide a unique opportunity for the search of the Higgs boson in the mass range from 110 to 200 GeV until new LHC data arrives. At the same time, a wide range of other physics topics will be present. Among these we expect to study various rare decays of B mesons, search for CP violation and $B_{d,s}$ oscillations. In this note we discuss various aspects of Standard Model (SM) Higgs production and B physics in Run II.

2 Experimental Layouts

Details of the DØ detector can be found elsewhere [1]. Here, we briefly summarize the main features of the detector relevant for Higgs and B physics. The heart of the DØ detector is a silicon tracking system (SMT), which consists of six barrel segments with disks in between and three more disks located at each end of the tracker. The barrel and disks are based on 50 μm pitch silicon microstrip detectors, providing spatial resolution $\sim 10\mu m$. At each end of this system the two large disks are placed in order to increase η_{det} coverage. The SMT system is enclosed in fiber tracker (CFT). They represent a complete robust tracking system of the detector. DØ detector will allow us to have momentum resolution at the level of $\sigma(p_T)/p_T = 0.02 - 0.05$ for low p_T tracks with quite high tracking efficiency for charged particles at $|\eta_{det}| < 3$. Vertex reconstruction resolution is expected to be $15 - 30\mu m$ in $(r - \phi)$ plane for primary vertices and for secondary vertices it is expected to be $40\mu m$ in the $(r - \phi)$ and $100\mu m$ in the $(r - z)$ planes, respectively. A major upgrade of the muon system together with central and forward scintillators will allow us to trigger charged tracks. Electron and muon identification will be possible in the central and forward regions.

The CDF detector has similar capabilities such as a new silicon and central outer trackers, plug calorimeter, muon chambers, and data acquisition system. Owing an additional silicon layer near the beam pipe, a time of flight system, they are expect to have slightly better vertex reconstruction resolution [2].

3 Higgs Production at the Tevatron

In the Standard Model, Higgs bosons are expected to be produced in gluon fusion or in conjunction with a W or Z boson. The expected cross sections at the Tevatron are shown in Fig. 1 [3]. Although the gluon fusion mode is expected to be largest contributor to Higgs boson production, it will be overwhelmed by the huge QCD background. Therefore pay most attention to the WH and ZH production modes. The

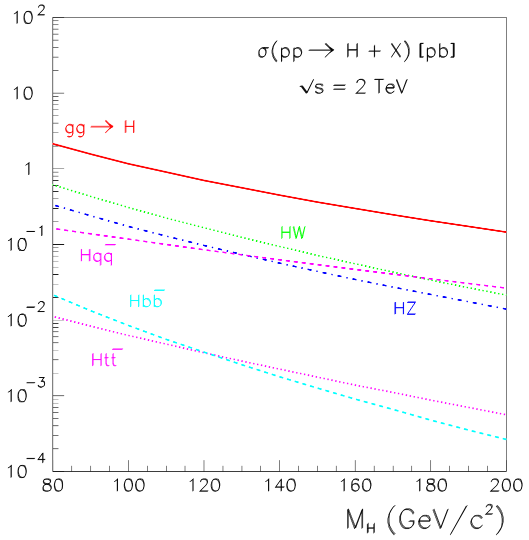

Figure 1: The SM Higgs cross section for six production modes versus Higgs mass.

Higgs boson will mainly decay into $b\bar{b}$ and WW final states for the mass range below and above 135 GeV, as shown in Fig. 2 [3].

In the low mass range, $m_H \simeq 90 - 130$ GeV, in 90% of the cases the Higgs will decay into a $b\bar{b}$ pair giving a $(q\bar{q}, \ell^+\ell^-, \ell\nu, \nu\bar{\nu})b\bar{b}$ final state where the leptonic decay of the W or Z will serve as a trigger. The high-p_T lepton (e or μ) trigger is expected to use in selection of HW mode where $W \to \ell\nu$. We assume that such a trigger will be efficient for leptons with $p_T \geq 20$ GeV. Also a large amount of missing transverse energy $\not{E}_T \geq 20$ GeV is expected. Two b-tagged central jets are expected to survive in the "loose" and "tight" selection cuts. The main background for this mode will be $Wb\bar{b}$ and WZ decays. For the $\nu\bar{\nu}b\bar{b}$ final state the selection criteria are based on missing transverse energy from the escaping neutrinos and two distinct b-jets. Here the main backgrounds come from $Zb\bar{b}$ and ZZ events. For the $\ell^+\ell^-b\bar{b}$ final state, the trigger threshold for final leptons could be reduced to $p_T \geq 10$ GeV. The invariant mass of two outgoing leptons should be consistent with Z boson mass. Two separate b-jets are also required in this case. The main background will come from real Z's produced in conjunction with $b\bar{b}$ pairs, or from W's decaying hadronically. Finally, for the $q\bar{q}b\bar{b}$ case, the expected background from QCD events is expected to be unreduceable. The cross sections of di-jet and four-jet events are expected to be of the order of $\mathcal{O}(10^6)$ and $\mathcal{O}(10^4)$ pb, respectively.

For the mass range, $m_H \simeq 120-190$ GeV, where the Higgs boson produced in conjunction with a vector bosons, it will mainly decay into W^*W^* states [1] with subsequent decay $(W,Z)W^*W^* \to \ell^\pm\nu\ell^\pm\nu jj$. For this case selection criteria requires two leptons with $p_T \geq 10$ GeV having the same charge and two separate jets with $p_T \geq 15$ GeV and at least 10 GeV $\not{E}_T$. The main background in this case is $WZjj$ production. Also it is possible to consider tri-lepton final states produced in $W^\pm H \to \ell^\pm\nu W^*W^* \to\to \ell\nu\ell\nu\ell\nu$ chain. The main attraction of this case is a small background. One could find the best combination of trileptons and fit their invariant masses to be consistent with $W^\pm W^*W^*$ and $W^\pm W^*Z^*$ final states. Nevertheless we do not expect much to gain from this channel due to its small branching fraction.

In the case of gluon fusion production of the Higgs boson the four possible combinations are allowed:

$$
\begin{aligned}
H &\to W^*W^* \to \ell\nu jj \quad \text{and} \quad \ell^+\ell^-\nu\bar{\nu}, \\
H &\to Z^*Z^* \to \ell^+\ell^- jj \quad \text{and} \quad \ell^+\ell^-\nu\bar{\nu}.
\end{aligned}
$$

For the $\ell^+\ell^-\nu\bar{\nu}$ channel we expect to have a large background from WW, WZ, ZZ, and $t\bar{t}$ production. It can be reduced requiring two leptons with $p_T \geq 10$ GeV and η_{det} constrain. One could possible use a

[1] Hereafter, the $W^*(Z^*)$ denotes a $W(Z)$ boson of either on- or off-mass-shell.

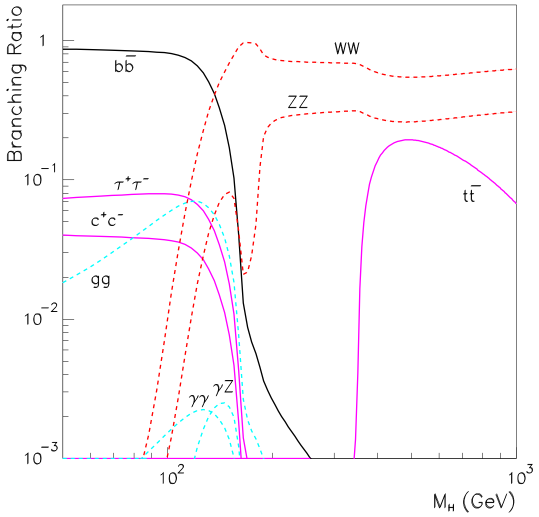

Figure 2: The branching fractions of various decay modes of the SM Higgs versus its mass.

transverse and a "cluster mass" mass constrains and perform likelihood analysis, see [4]. The rest of the two final states can be considered using proper cut for outgoing leptons and requiring two distinct jets.

Among various analyses underway in both collaborations, the most promising ones are based on a neural networks technique. Various sets of kinematic variables is used to discriminate signal from background. Among them are transverse momentum of the isolated lepton, its pseudorapidity, the missing transverse energy of the event, the invariant mass of the final $b\bar{b}$-pair, and the separation between the b-tagged jets, the lepton and the first b-tagged jet, and between the lepton and the second b-tagged jet. One of the important tasks is to find the best possible b-tagging efficiency and mass resolution which are expected to be at the level of 55-60% and 10%, respectively. It looks like that it will be impossible to choose a golden channel, and that success in a Higgs search will require a combination of all possible channels. The details of various techniques as well as latest results for Higgs search can be found in Ref. [4] and/or under web [5]. As a result of preliminary analyses, we show in Fig. 3 the integrated luminosity delivered per experiment which would be required to either exclude the SM Higgs at the level of 95% or to make a discovery at the 3σ and 5σ levels. The wide bands in the plot represent the

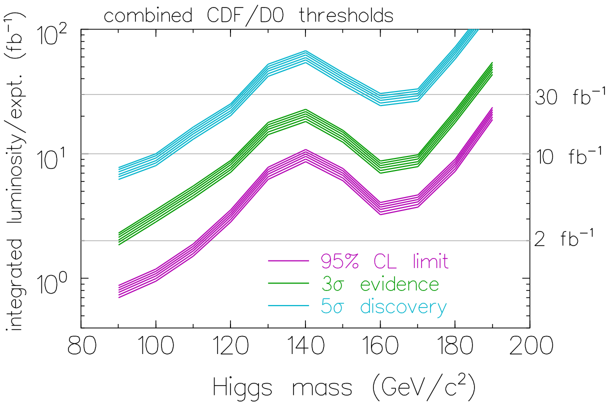

Figure 3: Integrated luminosity delivered per experiment required to either exclude at 95% C. L. (bottom curve) or discover the SM Higgs at the 3σ (middle curve) or 5σ (top curve) level as a function of Higgs mass. The theoretial uncertainties are already included in all curves.

calculated threshold plus uncertainties in the b-tagging efficiency, background rate, mass resolution, and other effects. As the plot shows, in order to cover the full possible spectrum of Higgs mass allowed at Tevatron energies, the total integrated luminosity should be extended up to 30 fb^{-1} per experiment. Even though a combination of all channels as well as the data from both experiments are needed, new approaches and robust reconstruction algorithms will also be required.

4 B physics at the Tevatron

The weak decays of B_d and B_s mesons play crucial roles in the study of CP violation effects both within and beyond the Standard Model. The CKM [6] matrix elements, determined from various B decay channels, can be represented in the Wolfenstein parameterization [7] as a set of four parameters A, λ, ρ, η. The parameters A and λ are known with good accuracy [8]:

$$\lambda = 0.2196 \pm 0.0023, \quad |V_{cb}| = (39.5 \pm 1.7) \times 10^{-3} \quad A = \frac{|V_{cb}|^2}{\lambda^2} = 0.819 \pm 0.035.$$

The ρ and η parameters can be extracted mostly from four processes: CP violation in the neutral kaon system, oscillations of B_d^0 and B_s^0 mesons, and charmless semileptonic b decays. The last three of these are the subject of great interest in the Run II B physics program.

The expected luminosity of the Tevatron, 2×10^{32} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$, in Run II will lead to a huge rate of $b\bar{b}$ production, $\sim 10^{11}$ events/year. This enormous statistics will allow us to study various B decays modes, search for CP violation and $B_{d,s}$ mixing. Primary interest will focus on the study of CP-violation, and related constraints on $|V_{td}/V_{ts}|$ from B_s mixing. Oscillations in B system occurs because of high-order corrections, as shown in Fig. 4. The light and mass eigenstates, B_L and B_H, are different from the CP

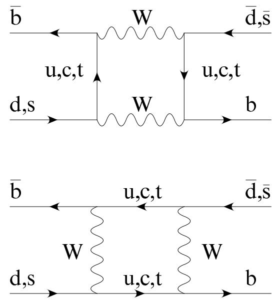

Figure 4: Feynman diagrams responsible for mixing in the B systems.

eigenstates B_q^0 and $\overline{B_q^0}$:

$$|B_L\rangle = p|B_q^0\rangle + q|\overline{B_q^0}\rangle \quad |B_H\rangle = p|B_q^0\rangle - q|\overline{B_q^0}\rangle, \quad q = d, s \text{ quarks}.$$

Unlike the kaon system, the mass difference $\Delta m_q = m_{B_H} - m_{B_L}$ is the key feature of the physics. Many analyses of $B_d^0 - \overline{B_d^0}$ oscillations have been performed by several collaborations and their results have been combined to give [9]: $\Delta m_d = 0.472 \pm 0.017$ ps^{-1}. For the case of B_s^0 mesons, due to their large mass difference Δm_s, the B_s^0 oscillation frequency is thought to be much higher then the well measured B_d^0 one. Existing data, mostly from CERN experiments, exclude small values of the mixing parameter x_s, $x_s = \Delta m_{B_s^0}/\Gamma_{B_s^0} > 14.0$ at the 95% CL [9].

Various decay modes of B_s^0 mesons are under investigation by the DØ collaboration. Among them

$$\begin{aligned}
B_s^0 &\rightarrow D_s^-(K^-K^+\pi^-)\pi^+, && (B = 1.1 \times 10^{-4}),\\
B_s^0 &\rightarrow D_s^-(K^-K^+\pi^-)3\pi, && (B = 2.8 \times 10^{-4}),\\
B_s^0 &\rightarrow J/\Psi K^*, && (B = 5.1 \times 10^{-6}),\\
B_s^0 &\rightarrow D_s^-(K^-K^+\pi^-)\ell^+\nu, && (B = 1.1 \times 10^{-4}).
\end{aligned}$$

The final data sample will be determine by the quality of the track and secondary vertex reconstruction algorithms. Final states of B's are expected to be fully reconstructed and tagged by the charge of the lepton and reconstructed charm meson and/or kaon. The initial state required for a B_s mixing search can be tagged in one of two possible ways, either by applying same-side tagging or opposite-side tagging techniques. Using the good SMT resolution, we can tag B decays using displaced secondary vertices or tracks with large impact parameters. For a 10% B reconstruction efficiency and with 12% of B_s having $p_T > 0.5$ GeV and $|\eta_{det}| < 1.5$ for all final state particles, we expect approximately 2500 reconstructed events. We will be sensitive for $x_s \leq 20$. A new limit for $|V_{ts}/V_{td}|$ can be establish using the well-known relation:

$$\frac{\Delta m_s}{\Delta m_d} = \frac{m_{B_s^0}}{m_{B_d^0}} \xi^2 \left| \frac{V_{ts}}{V_{td}} \right|^2 = \frac{m_{B_s^0}}{m_{B_d^0}} \frac{\xi^2}{\lambda^2} \frac{1}{(1-\rho)^2 + \eta^2},$$

where theoretical uncertainties are included in the quantity ξ [10, 8]:

$$\xi = \frac{f_{B_d} \sqrt{B_{B_d}}}{f_{B_s} \sqrt{B_{B_s}}} = 1.14 \pm 0.08.$$

The CDF detector is expected to obtain a better constrain on the x_s parameter. Using their time-of-flight system, K/π separation at the level of 2σ and opposite kaon tagging, they expect to reach $x_s \sim 60$ [11].

A second major component of the B physics studies will be a CP violation search in B decays. It is well known that an asymmetry in the B system is generated if both decay amplitudes are nonzero and if the weak decay phase, ϕ_{decay}, is different from the mixing one, ϕ_{mixing}. Defining mass eigenstates as $|B_1\rangle = p|B^0\rangle + q|\overline{B^0}\rangle$ and $|B_2\rangle = p|B^0\rangle - q|\overline{B^0}\rangle$ we have the following definition of ϕ_{mixing} and ϕ_{decay}:

$$\frac{q}{p} = \sqrt{\frac{m_{12}^* - i\Gamma_{12}^*/2}{m_{12} + i\Gamma_{12}/2}} \simeq \frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*} = e^{-2i\phi_{mixing}}, \quad \bar{\rho}(f) = \frac{\langle f|H|\overline{B^0}\rangle}{\langle f|H|B^0\rangle} = \eta_f e^{-2i\phi_{decay}}$$

Experimentally, we need to look for the asymmetry of the final state, f:

$$A_{CP}(t) = \frac{\Gamma\left(\overline{B_q^0} \to f\right) - \Gamma\left(B_q^0 \to f\right)}{\Gamma\left(\overline{B_q^0} \to f\right) + \Gamma\left(B_q^0 \to f\right)} = \sin(2\beta)\sin(\Delta m_q t),$$

and try to measure the quantity $A_{obs} = D_{mix} D_{tag} D_{bgd} A_{CP}$. Here the dilution factor $D_{tag} = 1 - 2p_{misstag}$ is defined via the correct tag probability $p_{misstag}$ and together with efficiency ε defines the tag's effectiveness, εD_{tag}^2; where the mixing factor $D_{mix} = \sin(\Delta m_q t) = x_q/(1+x_q)$ and $D_{bgd} = \sqrt{S/(S+B)}$. The uncertainties on $\sin 2\beta$:

$$\sin 2\beta = \mathrm{Im}\left[-\left(\frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*}\right) \left(\frac{V_{cs}^* V_{cb}}{V_{cs} V_{cb}^*}\right) \left(\frac{V_{cd}^* V_{cs}}{V_{cd} V_{cs}^*}\right) \right],$$

are defined as

$$\delta(\sin 2\beta) = \frac{1}{D_{mix} D_{bgd}} \sqrt{1/(\varepsilon D^2)_{tag} N_{rec}},$$

where N_{rec} is the number of reconstructed events. The three major blocks in $\sin 2\beta$ comes from $B^0 - \overline{B^0}$ mixing, $\left(\frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*}\right)$, final decay fraction $\bar{\rho}(f)$, $\left(\frac{V_{cs}^* V_{cb}}{V_{cs} V_{cb}^*}\right)$ and $K^0 - \overline{K^0}$ mixing, $\left(\frac{V_{cd}^* V_{cs}}{V_{cd} V_{cs}^*}\right)$. Flavor tagging efficiency will play a crucial role in final purity of the samples. We have summarized it in Table 1. All numbers are based on our knowledge from Run I and MC studies. As can be seen from the table our tag effectiveness will not exceed 10%. The golden mode is expected to be the decay of $B \to J/\Psi + K$ which is quite easy to trigger when $J/\Psi \to \ell^+\ell^-$. The following cuts can be applied in this case: $p_T > 1.5$ GeV for muon tracks, $p_T(K) > 0.5$ GeV and $|\eta_{det}| < 2$. We expect to have approximately 40000 $B^\pm \to J/\Psi + K^\pm$ and 20000 $B^0 \to J/\Psi + K^{0*}$ events with statistical errors dominating the systematics. For the time-independent analysis, assuming 2 fb^{-1} integrated luminosity, $S/B \simeq 0.75$, and a tag effectiveness $(\varepsilon D^2)_{tag} \simeq 9.8\%$, our expectation leads to $\delta(\sin 2\beta) \simeq 0.04$ for the case of $J/\Psi \to \mu^+\mu^-$ and $\delta(\sin 2\beta) \simeq 0.05$ for the $J/\Psi \to e^+e^-$ channel. With 20 fb^{-1} we will go down to $\delta(\sin 2\beta) \simeq 0.01$.

Tag	$\varepsilon D^2(\%)$ measured CDF Run I	$\varepsilon D^2(\%)$ expected CDF Run II	Relevant DØ difference	$\varepsilon D^2(\%)$ DØ capabilities
same side	$1.8 \pm 0.4 \pm 0.3$	2	same	2
soft lepton	$0.9 \pm 0.1 \pm 0.1$	1.7	μ, e ID coverage	3.1
jet charge	$0.8 \pm 0.1 \pm 0.1$	3	forward tracking	4.7
opp. side		2.4	no K id	none
combined		9.1		9.8

Table 1: Flavor tagging efficiencies for both CDF and DØ detectors based on knowledge from Run I and MC studies [12].

Such precision, together with other measurements, will tune the position of the unitary triangle in the $\rho - \eta$ plane and help us better understand the SM parameters.

Among other possibilities a large area of B physics can be covered in Run II: individual hadron masses and lifetimes ($B^{\pm}$, B^0, B_s, Λ_b) search for B_c meson ($B_c \to J/\Phi + \pi$) search for rare b-decays ($b \to X_s \ell^+ \ell^-$, $b \to \ell^+ \ell^-$, $B_s \to K^* \gamma$, $B_s \to D_s^{*+} D_s^{*-}$), and a non-SM CP violation search via the $B_s \to J/\Psi + \phi$ channel, but they are out of topic of this discussion.

5 Conclusion

As we have shown, the forthcoming Run II at the Tevatron collider is expected to give us a unique opportunity to study various exciting aspects of the SM, such as Higgs search and CP violation. Thanks to the huge effort from many people, the DØ and CDF detectors are on the final road and ready to start collecting data in March 2001. The main improvements in Run II that make us optimistic for the physics are based on increased integrated luminosity, at least factor of 20x more then in Run I, and major upgrades of both detectors. For both goals, Higgs search and B physics, the main gains will come from b identification and from the $b\bar{b}$ invariant mass measurement. Now our focus is concentrated on building a robust, reliable reconstruction algorithm, in order to fully explore the detector capabilities. Preliminary studies by the Higgs search working group show that there is no golden channel in the analysis, and in order to be successful, we need to combine all data and all decay modes from both experiments. Initial luminosity of the Tevatron, 2 fb^{-1}, will allow us to explore Higgs mass at the level of LEP2, but with 10 fb^{-1}, we will be able to exclude at 95% C.L. an SM Higgs up to $\sim$ 180 GeV and with 20 fb^{-1} we could see its evidence at the level of 3σ. DØ and CDF will significantly contribute to B physics in Run II. The main focus of our attention will be the B_s oscillation search and CP violation. Several different modes are under investigation. We expect to improve the lower limit on the x_s parameter up to a level of 20 (DØ) and 60 (CDF) and extend our knowledge about the unitary triangle by measuring $\sin 2\beta$ with an accuracy of 0.01-0.05.

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