Standard Model Physics at the Tevatron

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Abstract. The CDF and DØ collaborations at the Tevatron have been producing exquisite precision measurements on high-P_T physics with their large datasets of $p\bar{p}$ collisions. The Higgs boson is being sought in all available channels, and the Tevatron experiments will have a chance to discover it before LHC starts operating. The top quark is being studied in great detail, and a precision of 1.2% in the measurement of its mass has been achieved. In this brief report an overview of the most interesting topics will be given.

1. The facilities

The Tevatron accelerator has been subjected at the turn of the millennium to a massive upgrade, with the construction of an entirely new ring, the Main Injector, and several improvements in the facility producing and storing antiprotons – the most challenging part of the whole project. The collider has recently surpassed the peak luminosity of $2.3 \times 10^{32} cm^{-2} s^{-1}$. An integrated luminosity of $2.0 fb^{-1}$ has been delivered to CDF and DØ so far, and 5 to 8 inverse femtobarns are expected by end of 2009. Up-to-date information on the performance of the machine can be found in [**?**].

An overview of the CDF and DØ detectors for Run II at the Tevatron can be found in [1]. In what follows their most important features for high-P_T physics are briefly mentioned.

Both detectors are all-purpose, near-hermetic devices consisting of a tracker immersed in a solenoidal field and an outer shell of calorimeters and muon chambers.

In DØ an excellent system of silicon microstrip detectors has been installed in Run II. Six barrels of silicon sensors organized in four concentrical layers provide coverage for central tracks, while a total of sixteen silicon disks allow reconstruction of large rapidity tracks. A similar set of seven barrels of silicon strips is organized in the core of CDF.

Outside of the silicon barrels CDF features a large gas tracking chamber, and DØ has a compact scintillating fiber tracker. Both allow measurement of track momenta with better than percent accuracy for $P_T < 100 GeV$. Associated hits in the silicon strips allow the determination of track impact parameter with accuracy sufficient to reconstruct B-hadron decay and enable $\sim 45\%$ efficient tagging of b-quark originated jets with fake rates well below 1%.

Calorimeters are divided in a inner electromagnetic and an outer hadronic section. Electrons within the pseudorapidity interval $|\eta| < 2.0$ are identified with high purity and efficiency, with a resolution of $14\%/\sqrt{E}$ in CDF and $17\%/\sqrt{E}$ in DØ. Hadronic jets are reconstructed with resolutions better than $100\%/sqrtE$. Muon chambers cover the rapidity region $|\eta| < 1.5$ in CDF and $|\eta| < 2.0$ in DØ .

Both detectors have a sophisticated trigger system that reduces the 2.5MHz collision rate to about 100 Hz of events written to tape. Of particular relevance for the present review is the Silicon Vertex Tracker (SVT), a device designed and built in CDF to achieve precise online tracking. The SVT identifies track candidates by comparing hit patterns to a predetermined array of possible roads stored in associative memory banks. A linearized $R-\phi$ fit of track hits in the silicon layers provides track momentum and impact parameter with precision close to that attainable offline in less than $10\mu s$, thanks to a highly parallelized architecture. This allows the collection of datasets based on the presence of b-quarks in the final state, enhancing the B-physics program of CDF but also providing higher efficiency for several Higgs boson signatures.

2. Searches for the Standard Model Higgs boson

The search for the Higgs boson at the Tevatron is carried out by looking for its two main decay signatures, depending on the particle mass: if $M_H < 135$ GeV the dominant decay is $H \to b\bar{b}$, while at higher masses the $H \to WW$ decay provides the most promising signature.

Both CDF and DØ search their datasets for WH and ZH associated production with a low mass higgs boson decaying to a pair of b-quark jets, while the vector boson is tagged by the reconstruction of two charged leptons (for $Z \to ee$ or $\to \mu\mu$), a lepton and missing transverse energy (to select $W \to e\nu$ or $\to \mu\nu$), or missing transverse energy alone (for $Z \to \nu\nu$ decays). The two critical parameters affecting signal significance are the efficiency of b-quark jet identification -performed through the reconstruction of a secondary vertex in the jet- and the resolution of a reconstructed dijet mass peak. The dijet mass distribution is studied in search for an excess over backgrounds, which are mainly due to real vector boson production associated with jets from QCD radiation and top quark production (see Fig. 1, left).

If the Higgs mass is higher than 135 GeV, its WW decay becomes dominant. In that case, both direct production and associated production of a Higgs and an electroweak boson -yielding three vector bosons in the final state- are promising search channels.

In direct $H \to WW$ searches, when both W bosons decay to an electron-neutrino or muon-neutrino pair the final state is quite clean, with reducible backgrounds mostly due to Drell-Yan production of lepton pairs. To discriminate direct production of a Higgs boson from non-resonant WW production - which in the standard model has a sizeable cross section [2] – it is useful to study the azimuthal angle $\Delta\Phi_{ll}$ between the two charged leptons (Fig. 1, right), since the zero spin of the Higgs boson and helicity conservation conspire to produce leptons in the same direction in the transverse plane.

The sum of all known processes accounts nicely for the number of events found in each search channel, and 95% limits are set to the production cross section of the Higgs boson as a function of its mass. Figure 2 summarizes the present status of Higgs boson searches at the Tevatron. It is necessary to note that most searches are still based on relatively small amounts of data, while larger datasets still are being analyzed. The standard model prediction for Higgs production appears still far away: nevertheless, results are still roughly in line with what was predicted by the 2003 Higgs sensitivity study [**?**]. That study foresees that by the end of 2009 a light Higgs boson is likely to be discovered at the Tevatron, or excluded for all masses below 135 GeV. In order to reach that goal, a combination of all results by CDF and DØ is mandatory. The two experiments are collaborating well in these searches, and new limits will be produced as more data is analyzed.

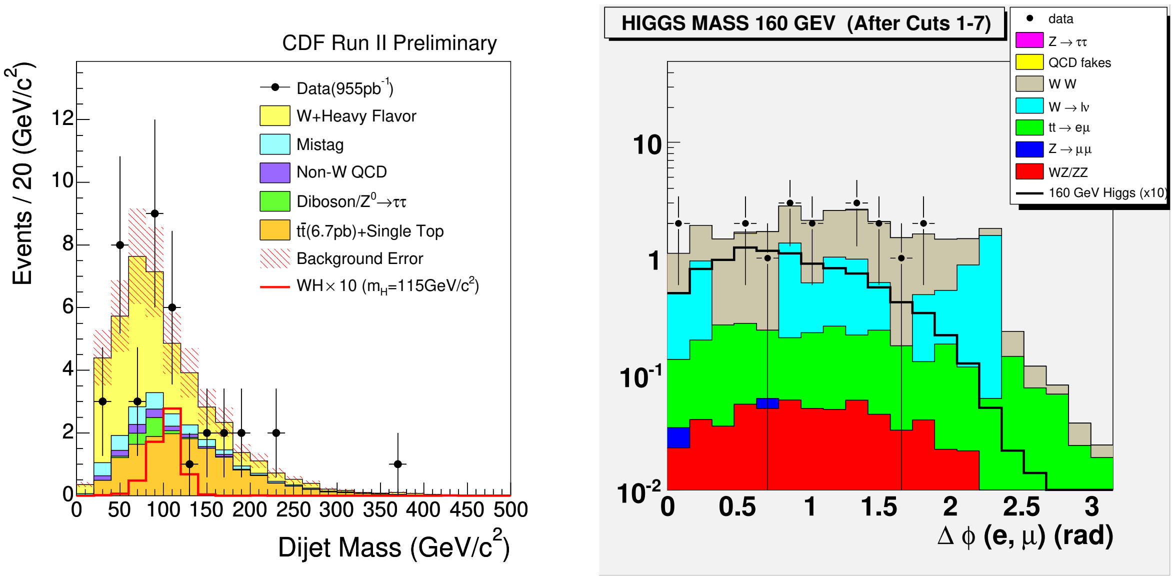

Figure 1. *Left: dijet mass distribution of b-tagged jets in WH candidate events collected by CDF in $955pb^{-1}$ of run 2 data. Right: azimuthal angle between the two charged lepton candidates in the dielectron final state of the DØ $H \to WW$ analysis.*

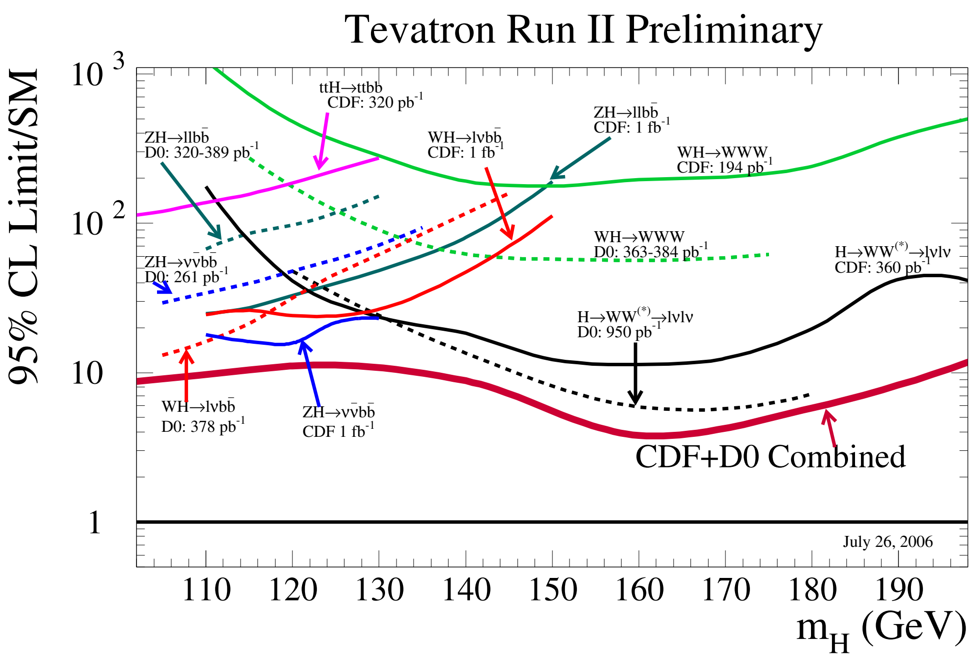

Figure 2. *Summary of 95% C.L. limits on the ratio of Higgs boson cross section divided by SM expectations, for all studied search channels. Individual limit curves obtained by the different analyses are shown, together with the combined limit of all displayed CDF and DØ searches.*

3. Top quark measurements

The large datasets of $p\bar{p}$ collisions collected by CDF and DØ allow for many precision measurements of top quark properties. Top quarks are particularly interesting as laboratories

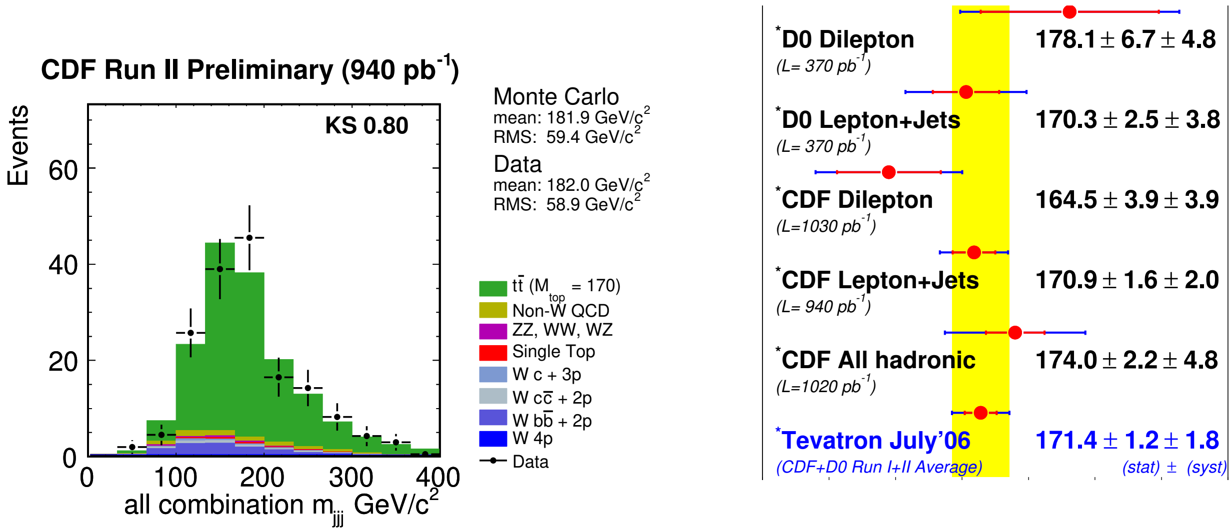

Figure 3. Left: Reconstructed top quark mass in the CDF lepton+jets matrix element analysis. Right: summary of the best results on the top mass obtained by the CDF and DØ collaborations and their combination.

of perturbative QCD, because of their large mass and short lifetime. The most interesting measurement is however the one of the top mass, which is a fundamental parameter of the standard model and has a large impact through radiative corrections in the global fits to electroweak observables attempting to verify the internal consistency of the model and predict the unknown mass of the Higgs.

There are by now tens of determinations of M_{top}, using different techniques and final states of top quark pair production. The single most precise measurement has been obtained by CDF by reconstructing the top mass in the single lepton final state of top pair production from $940 pb^{-1}$ of collisions, resulting in 166 events containing a high-P_T lepton, missing transverse energy, and four jets, one of which originated by b-quark hadronization. A likelihood is calculated for each event using the matrix element for leading order top pair production and a parametrization of parton showering yielding the observed jets. The final measured top mass is then extracted from a joint likelihood of the product of the individual event likelihoods, where the jet energy scale uncertainty is convoluted with the statistical error using an in-situ measurement of the hadronic W boson mass. The use of the W mass as a calibration point allows to reduce the dominant source of systematics, and the final measurement is $M_{top} = 170.9 \pm 2.2 \pm 1.4 GeV$, where the first error is the statistical plus jet energy scale uncertainty, and the second accounts for all other systematics. Fig. 3 (left) shows the reconstructed W and top quark masses in the sample.

That measurement, along with selected others, has been combined into a world average of $M_{top} = 171.4 \pm 2.1 GeV$, which is accurate to 1.2% (see Fig. 3, right). Before the end of Run 2 the experiments are likely to get to a 1 GeV accuracy on the top quark mass.

4. Precision electroweak physics at the Tevatron

In the remainder of this paper it is only possible to mention one further recent result on high-P_T physics from the Tevatron experiments, namely the recent discovery of production of pairs of WZ bosons, a rare process of high relevance for Higgs searches. CDF obtained 16 WZ candidates by an optimized search for triplets of charged leptons and missing transverse energy in $1.1 fb^{-1}$

Figure 4. Left: The signal of WZ production discovered by CDF in the tail of the missing transverse energy distribution. Right: a candidate for ZZ production found by CDF.

of data, where only 2.7 events were expected from background processes. Figure 4 displays the distribution of the missing transverse energy in the events, showing the clear signature of WZ production at large missing E_T. Now one more process of that kind is still missing, associated ZZ production, and CDF observed one event with the required characteristics, it will take some more data to measure that process as well. The event display for the ZZ candidate is show in Fig. 4 (right).

5. Conclusions

The CDF and DØ experiments are producing remarkable physics results in high-P_T physics measurements with the large datasets of $p\bar{p}$ collisions they have collected so far during Run 2. If the Tevatron will provide the estimated luminosity of 5-8 fb^{-1} by the end of year 2009, there is a chance that the Tevatron will beat the LHC in the quest for the Higgs boson. One less ambitious and more certain target is reaching a precision in the top quark mass which will remain the most precise measurement for many years to come. CDF and DØ look forwards to the last few years of running with a lot of enthusiasm for the forthcoming challenges.

Acknowledgments
I wish to thank ...

References

[1] T.LeCompte and H.T.Diehl, *The CDF and DØ upgrades for Run II*, Ann. Rev. Nucl. Part. Sci. 50 (2000), 71.

[2] The latest measurement by CDF is $\sigma_{WW} = 13.6 \pm 2.8_{stat.} \pm 1.6_{syst.} \pm 1.2_{lum.}$, see hep-ex/0605066.