Highlights from the Tevatron

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On Behalf of the CDF Collaboration

Abstract — We discuss here some of the most recent and relevant measurements obtained at the Tevatron, mainly from the CDF Collaboration. Special coverage will be given to the methodologies used, the sensitivities and the results expected in the next future.

1 Introduction

The two Tevatron experiments, CDF and DØ , have explored in the last 15 years (and more in the case of CDF) the vast phenomenology of hadron collider physics, providing discoveries and measurements. These results have been achieved with the help of selected triggers, specific analysis tools and dedicated methodologies. In this paper we discuss some important results obtained in different sectors, and the sensitivity we could reach a couple of years from now when LHC will probably reach design performances.

Some of the techniques and metodologies employed by CDF and DØ might be fruitfully used by CMS and ATLAS future analyses. Also, some of these measurement will provide a benchmark to help calibrate their detectors and algorithms.

1.1 Tevatron performances

The Tevatron is a $p\bar{p}$ collider working at the highest center-of-mass energy currently reachable, $\sqrt{s} = 1.96$ TeV. With respect to the 1990-1996 conditions (i.e. the so-called Run I) the instantaneous luminosity has been incremented by one order of magnitude or more, mainly with the help of a recycler ring which enables higher antiprotons currents. During the last 5 years of the so-called Run II, the instantaneous luminosity has reached indeed a record peak of 2.2×10^{32} cm^{-2} s^{-1}. As of September 2006, the integrated luminosity delivered amounted to 1.7 fb^{-1} while the luminosity collected individually by the two experiments was only slightly smaller, 1.5 fb^{-1}. The statistics expected for the near future is of 4 fb^{-1} by the end of 2007 and, if the performance of the Tevatron remains the same, between 6 and 8 fb^{-1} by the end of 2009.

1.2 CDF and D0 detectors

Two detectors, named CDF [1] and D0 [2], sit at the two Tevatron collision points. With the inclusion of tracking in Run II for D0, the two detector have become quite similar, both featuring a solenoidal magnetic field, a silicon microvertex detector, electromagnetic and hadronic calorimeters and muon detectors. The trigger and the data acquisition systems have been designed with the capability of dealing with high rate triggers.

Given the similarities in the detectors, and the feed-back between collaborations, the analyses and measurements performed by the two collaborations are sometimes conducted with similar techniques and lead to similar results which, in the case of important quantities like the W boson or top quark masses, are indeed combined. In order to simplify the discussion and to avoid duplications, we will report here mainly on the CDF results.

1.3 The Tevatron physics program

The physics program conducted at the Tevatron is vast and embraces both the Standard Model and QCD phenomenology. Other exotic fields, like Supersymmetry, are being explored but no specific observation is currently made. A typical organization of the analyses (and also of the working groups) derives naturally from the production cross sections of different processes, as shown in Fig. 1. Processes with the highest cross section ($\sim$ 10 mb) concern inelastic processes. The corresponding sector is termed "QCD" and treats essentially the production of jets. Cross sections of the order of $\sim 10\mu$b are instead typical of the production of b-hadrons. The corresponding physics is named "heavy flavor physics" and deals with lifetimes, spectroscopy and also CP mixings and oscillations. Electroweak processes, like the production of W and Z bosons, occur with cross sections of about 1 to 10 nb, and represent the domain of the "electroweak physics". The top quark, discovered at the Tevatron, is produced in pairs, with an even smaller cross section, of about 7 pb; the production of single top is expected with about half the cross section and has not yet been observed. "Top physics" is named the corresponding sector. New and exotic phenomena might appear with cross sections of the order of 1 pb or less and are generically considered under the "New physics" label. Most important of all in this set is the "Higgs boson search".

The program accomplished so far includes, among other things:

- the measurement of fundamental parameters of the Standard Model, like the mass of the W boson and of the top quark;
- the measurement of the production of heavy flavored hadrons, their spectroscopy and decay, lifetimes, branching ratio and the occurrence of B_d and B_s mixing and CP violation;
- the study of the parton distribution functions;
- the measurement of the cross sections for the production of W and Z bosons and of $t\bar{t}$ pairs;
- the search for new physics, including Supersymmetry, extra-dimensions and of course the search for the Higgs boson.

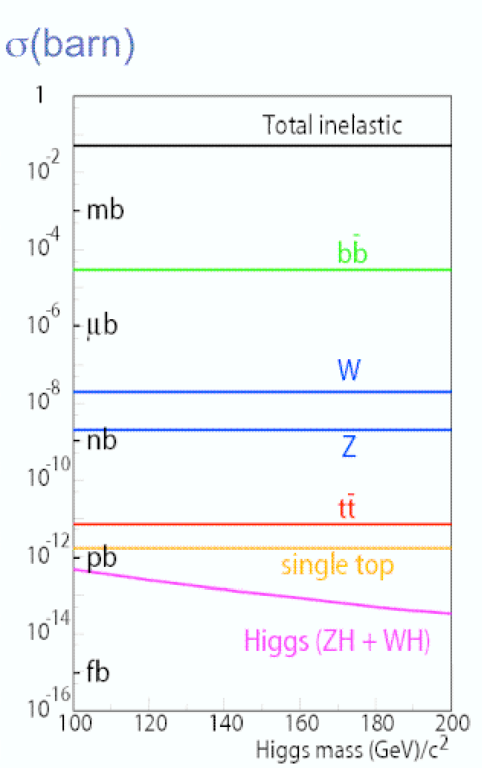

Figure 1: Typical cross sections for the main processes produced at the Tevatron (as a function of the Higgs boson mass).

2 Top physics

The discovery of the sixth quark, the top quark, by the CDF [3] and D0 [4] experiments in 1995, is one of the major achievements of physics at the Tevatron. That discovery has been achieved with only 110 pb^{-1}, corresponding to about 30 events per experiments. Now, 11 years later, the amount of data has increased by a factor of 10 and even more is expected by the end of the run, allowing precise measurements of the top quark properties like mass and cross section. Until the turn on of the LHC, the Tevatron will be the only place where one can study such properties.

At the Tevatron the top quark is produced mainly in pairs ($\sigma \approx 7$ pb); the production of single top is expected with smaller cross section ($\sigma \approx 3$ pb) and has not yet been observed. Apart from the most important quantities to measure, like the cross section and the top quark mass, studying the top production and decay provides insight into the possibility for new physics ($t\bar{t}$ resonances) or anomalous couplings, along with measurements of the CKM matrix element V_{tb}. The special interest devoted to the top physics lies in the fact that the top quark is indeed peculiar because it decays before hadronizing (unlike the 5 other quarks). This means we expect no spectroscopy, but on the other hand the spin of the top quark might be transferred to the decay products introducing correlations in the emission direction of the decay products. In addition, given its heavy mass, the top quark plays a main rôle in electroweak symmetry-breaking models, its mass being connected to the Higgs boson mass.

2.1 Cross section measurements

The measurement of $t\bar{t}$ the production cross section is important because is a test of the Standard Model, and deviations from what expected might be indication of new physics, like for instance the production of a resonant state $t\bar{t}$, or of the possibility for anomalous couplings.

The measurement of the cross section is in principle a simple task and consists in counting an excess of candidates, n, with respect to a predicted background, b:

$$\sigma_{t\bar{t}} = \frac{n-b}{\epsilon \cdot L}$$

where ϵ is the total selection efficiency and L the integrated luminosity. The challenge lies instead in selecting candidates with both a good efficiency and a good signal over background rate, S/B, and in the accurate estimate of the expected background.

Different topologies are defined considering the number of high-P_T leptons (basically e or μ) found in the final state. The "dilepton" topology (ee, $\mu\mu$ or $e\mu$) has tipically a negligible background but at the same time a small yield, given the small branching ratio, $BR = 9\%$. The "lepton + jets" topology has a larger rate ($BR = 30\%$) and a good S/B, representing the golden channel. The "all-hadronic" final state, with only jets and no high-P_T lepton has the largest yield ($BR = 44\%$) but unfortunately suffers from a huge background. To increase the collected signal a fourth topology has been considered, called "MET + jets", which requires large missing transverse energy, to cover the cases including one or 2 τ's in the final state (or when e or μ fail the identification cuts).

With the help of specific selections based on kinematical quantities (sometimes using neural networks) and on secondary vertex b-tagging, accurate measurement have been obtained for all different channels [5]. The accuracy reached at CDF on the cross section, see Fig. 2, is of about 14%. Combination with D0 measurements is underway.

If we consider the current sensitivities and extrapolate properly statistical and systematic uncertainties, the Tevatron goal for 2 fb^{-1} is a 10% precision on the cross section for each experiment.

2.2 Mass measurement

The top quark mass is not only a fundamental parameter of the Standard Model, but has the additional importance of entering electroweak radiative corrections providing tight constraints on the mass of the Higgs boson. The design goal for Run II was to reach a precision of 3 GeV/c^2 with 2 fb^{-1}. Such a goal has been already obtained with half the statistics. We expect now the Tevatron to reach a 1 GeV/c^2 precision even before LHC.

The measurement of the top quark mass is a difficult one because the final states contain several jets which need to be assigned to the quarks in the decay chain $t\bar{t} \rightarrow W^+bW^-\bar{b}$ where $W \rightarrow \ell\nu$ or $W \rightarrow qq'$. The inclusion of all assignment permutations of jets to quarks introduces a combinatoric background. This is made even more complicated by the inclusion of initial and final state radiation which leads to the production of additional jets. To overcome these (and other difficulties) several approaches have been introduced.

One approach, based on the "matrix element" technique, evaluates the probability that a given event, with given values for the kinematical quantities, is a signal event associated to a specific value of the top quark mass, M_t.

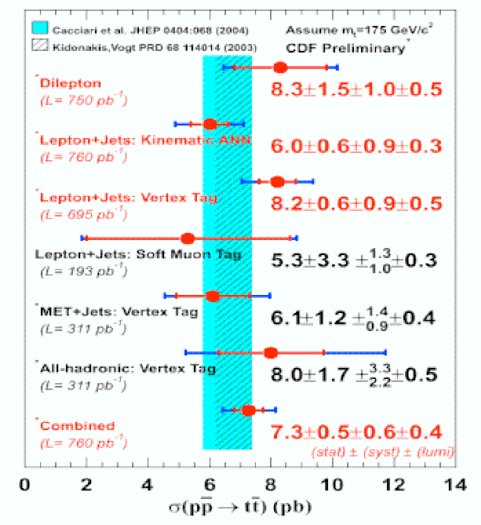

Figure 2: CDF measurement of the $t\bar{t}$ production cross section for different topologies.

Such probability is defined as

$$P_{top}(x, M_t, JES) = \frac{1}{\sigma} \int dq_1 dq_2 f(q_1) f(q_2) d\sigma(y, M_t) W(x, y, JES)$$

where $f(q_i)$ are the parton distribution functions, $d\sigma$ the differential cross section in terms of the true set y of kinematical quantities, and W represents the transfer function from the true set y to the measured set x. An important role in this definition is played by the uncertainty on the absolute jet energy scale which enters through the parameter JES. JES is a free parameter which can be constrained to provide the right W boson mass values. A similar probability, P_{bkd}, is defined for the background, removing of course the dependence from M_t. A global likelihood

$$\mathcal{L}(f_{top}, M_t, JES) \propto \prod_{i}^{N_{evts}} (f_{top} P_{top,i}(M_t, JES) + (1 - f_{top}) P_{bkd,i}(JES))$$

is defined as a function of the fraction, f_{top}, of signal events; through its maximization, over all candidate events, the best value of the top quark mass is obtained.

A different technique, called the "template method", uses the reconstructed top quark mass, as obtained from a kinematical fit minimizing (for instance in the "lepton + jet" case) a χ^2 quantity defined as:

$$\chi^2 = \sum_{i=1,4jets} \frac{(\hat{P}_T^i - P_T^i)^2}{\sigma_i^2} + \sum_{j=x,y} \frac{(\hat{P}_T^{UE} - P_T^{UE})^2}{\sigma_j^2}$$

$$+ \frac{(m_{jj} - M_W)^2}{\Gamma_W^2} + \frac{(m_{\ell\nu} - M_W)^2}{\Gamma_W^2} + \frac{(m_{bjj} - M_t)^2}{\Gamma_t^2} + \frac{(m_{b\ell\nu} - M_t)^2}{\Gamma_t^2}$$

where P_T^i are the measured values of the jet transverse momenta, P_T^{UE} are the x-y components of the underlying event, $\Gamma_W = 2.1$ GeV/c^2 is the natural width of the W boson and $\Gamma_t = 1.5$ GeV/c^2 is the assumed natural width of the top quark, and m are the 2- or 3-body invariant masses. The distributions for the reconstructed top quark mass for signal and background events become "templates" which model what expected from signal, see Fig. 3, and background events. These templates are translated into probability density functions which, for the signal, are parametrized in terms of the input top quark mass, and enter a likelihood function. The maximization of such likelihood in terms of the free parameters, the number of signal and background events, and the input top quark mass, for the set of candidate events provide the best value of the top quark mass. In the likelihod definition one might account for the JES uncertainty by including a template for the reconstructed W boson mass. In this case the constraint on the W mass will reduce drastically the systematic uncertainty related to the uncertainty on the jet energy scale.

The (currently) best CDF mass measurement is obtained in the "lepton + jets" channel with a simultaneous fit of the $W \to jj$ and $t \to bjj$ masses using a 2-dimensional template for the top quark mass and the deviation from

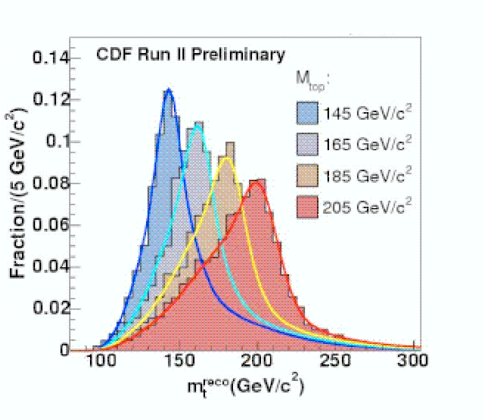

Figure 3: Reconstructed top quark mass templates for signal with different values of input top quark mass.

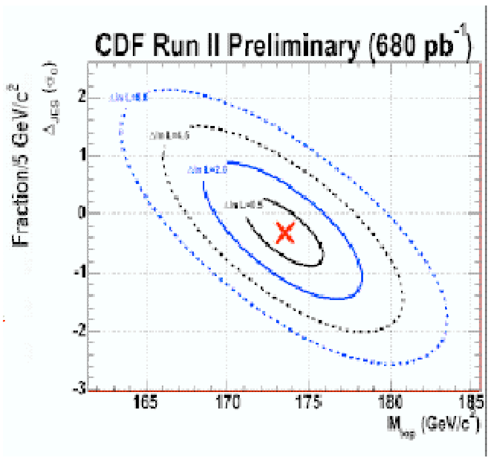

Figure 4: Δ_{JES} vs the fitted top quark mass for “lepton + jets” events.

the nominal jet energy scale, Δ_{JES}, as shown in Fig. 4. In this case CDF measures [6] $M_t = 173.4 \pm 2.5(stat. + JES) \pm 1.3(syst.)$ GeV/c^2.

The template method, in the 1-dimensional version with no JES fit , has been applied successfully to the difficult "all-hadronic" events, see Fig. 5, where CDF measures [7] $M_t = 174.0 \pm 2.2(stat.) \pm 4.8(syst.)$ GeV/c^2.

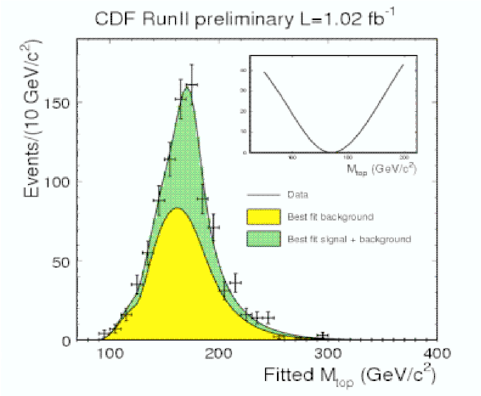

Figure 5: Fitted top quark mass compared to signal and background for "all-hadronic" events.

Other techniques and different channels have been exploited by CDF [8] and DØ [9] as shown in Fig. 6. The combined Tevatron measurement is $M_t = 171.4 \pm 2.1$ GeV/c^2 (including both Run I and Run II measurements, and accounting for correlations) with a 1.2% precision.

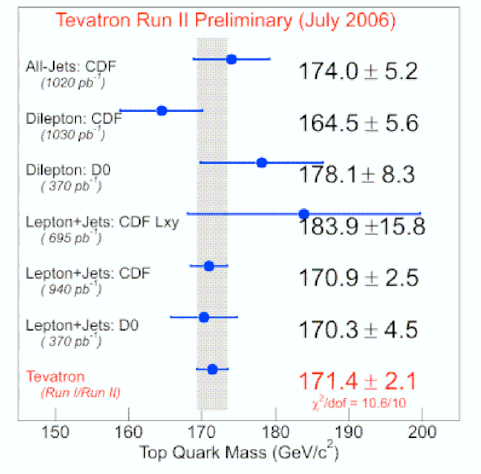

Figure 6: Top quark mass measured by CDF and D0 in different channels.

2.3 Single top

The single top production, via electroweak interaction, is actively studied, but represents a real challenge because of the lower yield and worse S/B with respect to pair production. In fact, the single top kinematics lies in between that for $t\bar{t}$ and background events. Sophisticated techniques are currently being employed, essentially using neural networks and multivariate likelihood functions, but so far no significant observation has been obtained. Exclusion limits are currently set, but CDF expects the capability of seeing a 3σ excess with 1.5 fb^{-1} (disregarding systematic uncertainties).

3 Heavy flavor physics

The latest achievement obtained by CDF in the sector of heavy flavor physics is represented by the measurement of B_s oscillations due the expected mixing of B_s and $\bar{B}_s$ states.

3.1 B_s mixing

To measure the B_s mixing 5 steps are needed (see Fig. 7):

1. Isolate as many B_s candidates as possible. This is obtained with the help of a trigger on secondary vertices.
2. Extract the B_s signal, considering exclusive hadronic decays (like $\bar{B}^0_s \to D^+_s \pi^-$) and inclusive semileptonic ones (like $\bar{B}^0_s \to D^+_s \ell\nu$). The decay flavor is inferred from the decay particles of the decaying B_s ("same-side tag", SST) or of the other B_s ("opposite-side tag", OST).
3. Measure the proper decay time, using precise measurement of the distance between primary and secondary vertices.
4. Define the B_s flavor at production time, using particle identification.
5. Measure the asymmetry, A, between mixed (same flavor for both B_s's) and unmixed (different flavor) events.

The asymmetry is defined as

$$A = \frac{P_{nomix} - P_{mix}}{P_{mix} + P_{nomix}} \propto \cos(\Delta m_s t)$$

where P_{nomix} (P_{mix}) represents the decay probability for events without (with) mixing, and is expected to oscillate as a function of the proper decay time t. The oscillation frequency is a measure of the mass difference, Δm_s, between the two B_s mass eigenstates.

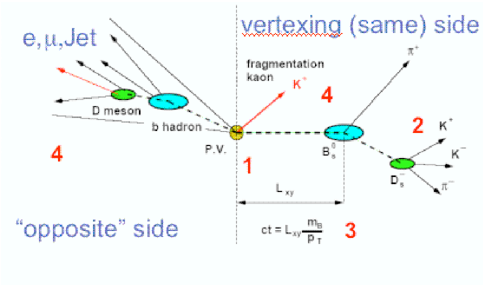

Figure 7: Schematics of the B_s mixing.

When measuring the observed asymmetry one needs to consider the effect of the detector in terms of efficiencies and resolutions. This reduces strongly the amplitude of the asymmetry, as shown in Fig. 8. With a Fourier-transform to the frequency domain, the amplitude is obtained for given values of Δm_s. A scan in Δm_s should give amplitude equal to one for the real Δm_s and amplitude equal to zero otherwise. From the scan shown in Fig. 9 CDF measures [10] $\Delta m_s = 17.77 \pm 0.10(stat.) \pm 0.07(syst.)$ ps^{-1}. The significance of the measurement is quantified as a 5.4σ effect. Such an observation is in agreement with a limit set previously by DØ [11] of $17 \leq \Delta m_s \leq 21$ ps^{-1} at 90% confidence level (a 2.5σ effect). This new B_s mixing measurement adds strong constraints to the CKM unitarity triangle.

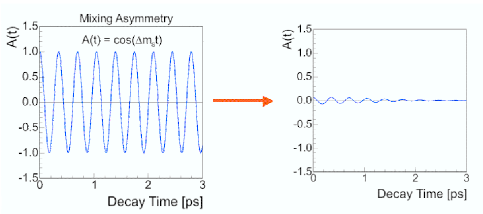

Figure 8: Asymmetry oscillation expected for an ideal detector (left) and a realistic one (right), as a function of the proper decay time.

3.2 Other measurements

Other important measurements in the heavy flavor sector include:

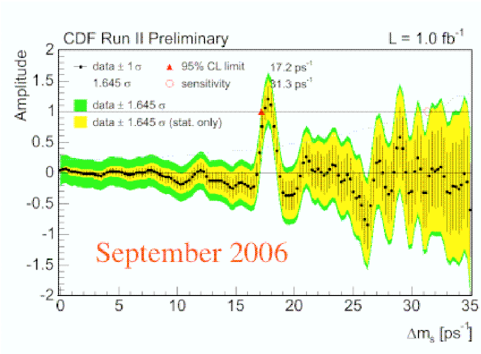

Figure 9: Amplitude scan, as a function of Δm_s.

- the spectroscopy of b-hadrons, the measurement of lifetimes and branching ratios;
- the observation of exclusive and rare decays;
- searches for flavor changing neutral currents.

4 Electroweak physics

One of the most important measurements in the electroweak sector is the measurement of the W boson mass. In fact the W boson mass, M_W, enters, together with the top quark mass, M_t, electroweak loop corrections linked to the mass of the Higgs boson. Very precise measurements of M_W and of M_t will give hints on the mass of the yet-to-be discovered Higgs boson.

4.1 Measurement of the W mass

The value of M_W is obtained from a precision fit of the Jacobian peak of the $\ell\nu$ transverse mass (see Fig. 10) and a major role in the measurement is played by a precise modeling of the recoil particles (i.e. what recoils off the W boson) and an accurate determination of all systematic uncertainties. Currently the LEP2 measurement of M_W is more precise than the Tevatron Run I measurement (100 pb^{-1}). The full Run II statistics has not been exploited yet, but the expectation is to reach soon (for 2 fb^{-1}) a sensitivity (per individual experiment) of the order of 20-30 MeV/c^2, see Fig. 11, better that the average LEP2 value of 35 MeV/c^2. These sensitivities have been obtained by extrapolating the Run I measurements and considering properly the uncertainties which scale with the luminosity (like the statistical uncertainties) and those which do not scale (like parton distribution function dependence and next-order theoretical calculations)

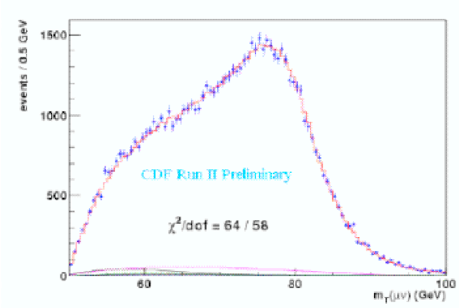

Figure 10: Transverse mass of the lepton-neutrino pair.

4.2 Additional measurements

Other important electroweak studies include

- the forward-backward asymmetry for the Z production;

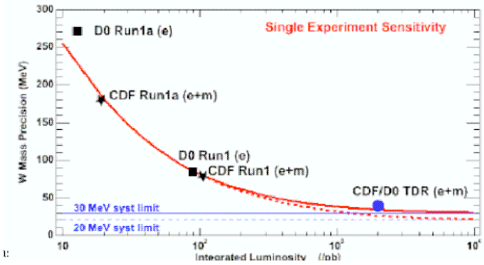

Figure 11: Sensitivity expected on M_W for each experiment.

- the charge asymmetry for the W production as expected from the V-A asymmetry, sensitive to u and d quark distributions;
- the direct measurement of the W width;
- the WW and WZ production, and the search for anomalous couplings.

5 QCD

One of the most important results in the QCD field is the study of the inclusive production of jets and the measurement of the corresponding cross section.

5.1 Inclusive jet production

Jets can be obtained clusterizing the energy deposit in the calorimetric towers with different algorithms (fixed cone, midpoint, K_T-algorithm). Each algorithm has different features, the midpoint one for instance has the benefit of being collinear/infrared safe, enabling a better comparison to the theory. Differential cross sections are measured [14] for instance for central jets (i.e. jets with rapidity smaller than 0.7 units and falling in the central portion of the calorimeters), as shown in Fig. 12. The agreement between the measurement and the next-to-leading order calculations is good over 8 orders of magnitude, providing support for the theoretical calculations and constraining the parton distribution functions.

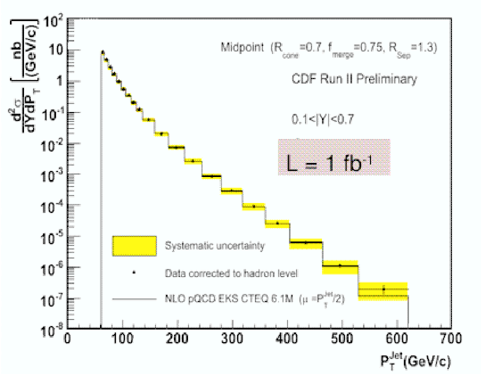

Figure 12: Differential cross section for the production of inclusive jets.

5.2 Additional studies

Other QCD processes of interest regard:

- the production of W or Z bosons in association to 1 or more jets;
- the b-jet cross section to study the goodness of NLO calculations;
- the production of high-P_T photons, with which one can constrain the gluon parton distribution function at high x.

6 Higgs boson search

A big effort is currently underway at CDF and D0 to search for evidence of the Higgs boson. At the Tevatron energies the cross sections for the production of the Higgs boson, alone or in association to other particles, is indeed very small, and decreases as the Higgs boson mass, M_H, increases. For instance for $110 \leq M_H \leq 140$ GeV/c^2 the associate production $WH + ZH$ has a cross section of about 100 to 300 fb. For such a mass interval the Standard Model dominant decay of the Higgs boson would be into a $b\bar{b}$ pair. The direct production $gg \to H$ has a one-order of magnitude larger cross section, but a $H \to b\bar{b} \to jj$ final state would be swamped completely by QCD multijet events. Only for $140 \leq M_H \leq 180$ GeV/c^2, when the decay $H \to WW$ dominates producing more than 2 jets, such production can be pursued with some hope.

The (low mass) signature of main interest are then:

- $ZH \to \nu\nu b\bar{b}$; the final state is expected to have no high-P_T lepton, large missing transverse energy (typically ≥ 100 GeV) and 2 b-jets. This channel is expected to be the one with highest yield.
- $WH \to \ell\nu b\bar{b}$; the final state contains one high-P_T lepton, significant (typically ≥ 50 GeV) missing transverse energy, and 2 b-jets. This channel has the highest production cross section, but we expect lower selection efficiency.
- $ZH \to \ell^+\ell^- b\bar{b}$; in this case we expect 2 high-P_T leptons forming the Z mass, and 2 b-jets. This is the cleanest channel.

Due to the very low cross sections, both experiments are not sensitive (yet) to observation and can only set exclusion limits, as shown in Table 1.

Table 1: Upper limits on the Higgs boson production cross section for CDF [12] and DØ [13] in different channels, for $M_H = 115$ GeV/c^2. Also shown, in parentheses, is the factor with respect to the Standard Model expectation.

Channel	**CDF**	**DØ**
$ZH \to \nu\nu bb$	1.1 pb (14)	3.4 pb (41)
$WH \to \ell\nu bb$	3.4 pb (23)	2.4 pb (16)
$ZH \to \ell\ell bb$	2.2 pb (27)	6.1 pb (75)

At present, about 25 different measurements performed by CDF and DØ in different channels, are being combined, using samples ranging from 200 to 1000 pb^{-1}. The 95% confidence level upper limit on the cross section, divided by the Standard Model cross section, is shown in Fig. 13.

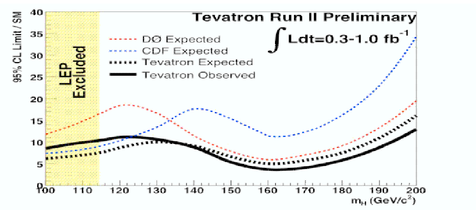

Figure 13: Upper limit on the cross section divided by the Standard Model cross section, as a function of M_H.

As seen in this plot, the Tevatron sensitivity is a factor of 5-10 above the Standard Model for $110 \leq M_H \leq 200$ GeV/c^2. We hope to increase the sensitivity by adding more statistics (a factor of 8 more data by 2009?), and applying known improvements to the current analyses, like extended coverage b-tagging and better jet resolution.

7 The femtobarn era

The physics program conducted at the Tevatron in the Standard Model frame is very rich and fruitful, and the statistics collected so far, about 1 fb^{-1}, enables CDF and DØ collaborations to make precise measurement of some fundamental quantities (like the top quark and W boson masses), while at the same time provides some sensitivity to rare or unexpected processes.

We have summarized here the most important results obtained in each one of the major physics sectors, i.e. "top physics", "heavy flavor physics", "electroweak" processes, "QCD" production and, last but not least, in the "Higgs boson search".

The expected new data, which hopefully will increase the available statistics by a factor of 8, along with future improvements in algorithms and tools, and with better calibrations of the detectors, should determine quite an increase in sensitivity to processes having cross sections of the order of 1 pb. Hopefully this will provide some hints on the Higgs and Supersymmetry sectors or on the search of new resonances. The CDF and DØ collaborations are dedicated to pursue with attention this exploration till the turn-on of LHC.

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