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REVIEW OF PHYSICS RESULTS FROM THE TEVATRON

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We present a comprehensive review of the physics results obtained by the CDF and D0 collaborations up to summer 2014, with emphasis on those achieved in the Run II of the Tevatron collider which delivered a total integrated luminosity of ~ 10 fb^{-1} at $\sqrt{s} = 1.96$ TeV. The results are presented in six main physics topics: QCD, Heavy Flavor, Electroweak, Top quark, Higgs boson and searches for New Particles and Interactions. The characteristics of the accelerator, detectors, and the techniques used to achieve these results are also briefly summarized.

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1. Introduction

Proton-antiproton ($p\bar{p}$) collisions are ideal to study elementary particle collisions at the highest energies, as was shown in the 1980's by the CERN $Sp\bar{p}S$ collider at $\sqrt{s}$=630 GeV, provided enough luminosity (driven mainly by anti-proton intensity) can be delivered.The Fermilab Tevatron,[1] a $p\bar{p}$ collider with superconducting magnets, went a step further in energy and luminosity, and operated from 1988 to 1996 at a center of mass energy of 1.8 TeV (Run I), and from 2001 to 2011 at a center of mass energy of 1.96 TeV (Run II). The CDF and D0 detectors each recorded approximately 0.1 fb^{-1} of collision data in Run I, and approximately 10 fb^{-1} of collision data in Run II. In the three years after the Tevatron's final shutdown in September 2011, the majority of the analyses have been completed, although a few important results, like the W mass measurement and Top properties, with the full statistics, are still in preparation. It is thus appropriate to provide now an almost comprehensive review of the main results, based on more than 900 published papers, to reflect the legacy of the Tevatron. A previous, shorter review was published in 2013.[2] The emphasis in this review is on Run II results, but the comparison with a summary of Run I results shows the progress which was achieved with a gain of two orders of magnitude in luminosity at approximately the same center of mass energy.

The review is organized in seven chapters: one introductory chapter briefly summarizing the experimental apparatus and the experimental techniques used, followed by six physics chapters, devoted to QCD, Heavy Flavor, Electroweak, Top quark, Higgs boson and searches for New Particles and Interactions.

1.1. *The Tevatron*

The Tevatron had its first collisions in 1985, and Run 0 took place from 1988 to 1989. The physics really started with Run I, which took place from 1992 to 1996 and provided sufficient collision data to produce a wealth of physics results.The center-of-mass energy of $\sqrt{s}$ = 1.8 TeV and a luminosity of up to 1.6 10^{31} cm^{-2} s^{-1}, provided an integrated luminosity of 0.1 fb^{-1}, and allowed for the discovery of the top quark.[3,4]

Extensive upgrades were performed from 1996 to 2001 on the accelerator, the main ones being to replace the Main Ring with the Main Injector in a new tunnel, and introducing a new Recycler Ring for antiproton storage with electron cooling to further reduce the beam phase space. Following these improvements, Run II began in 2001 at a center of mass energy of 1.96 TeV, and ended in 2011, when the Tevatron stopped operation on September 30. In all physics topics, major advances were achieved, as will be reviewed in the following chapters. The Tevatron delivered to the CDF and D0 detectors approximately 12 fb^{-1} of collision data in Run II, while approximately 10 fb^{-1} of excellent quality data were used in the "full statistics" analyses.

During Run II, the Tevatron achieved a maximum instantaneous luminosity of

4.31×10^{32} cm^{-2}s^{-1} but the effect of the overlay of multiple interactions remained manageable. Thirty-six bunches of protons collided with an equal number of bunches of antiprotons with a bunch spacing of 396 ns, spaced with gaps in order to allow kicker magnets to abort the beam cleanly. The luminous region had an RMS of approximately 25 cm along the beam axis and approximately 30 μm in the directions transverse to the beam axis The Tevatron accelerator complex is discussed in References 5, 6.

1.2. *The CDF and D0 Detectors*

The main components of the CDF[7,8] and D0[9–12] detectors are the tracking, calorimeters and muon detectors. Here we briefly summarize their main characteristics, together with their triggering systems specific to Run II.

The kinematic properties of particles and jets are defined with respect to the origin of the detector coordinate system which is at the center of the detector. To quantify polar angles the pseudorapidity variable, defined as $\eta = -\ln\tan(\theta/2)$, is used where θ is the polar angle in the corresponding spherical polar coordinate system. Throughout this review we use natural units, in which $c = \frac{h}{2\pi} = 1$.

1.2.1. *Tracking detectors*

The CDF tracking system consists of an eight-layer silicon microstrip tracker and an open-cell drift chamber referred to as the central outer tracker (COT), both immersed in a 1.4 T solenoidal magnetic field. These combined systems provide charged particle tracking and precision vertex reconstruction in the pseudorapidity region $|\eta| < 1.0$ with partial coverage in the COT to $|\eta| < 1.7$ while the two outer layers of the silicon detector extend the tracking capability to $|\eta| < 2.0$.

The D0 tracking system consists of an inner silicon microstrip tracker (SMT) surrounded by an outer central scintillating fiber tracker (CFT). Both the SMT and CFT are situated within a 1.9 T magnetic field provided by a solenoidal magnet surrounding the entire tracking system. The SMT is used for vertex reconstruction and for tracking up to $|\eta| < 2.5$, generally in combination with the CFT. The CFT is also used for tracking and vertex reconstruction, and provides precise tracking coverage up to $|\eta| < 1.7$.

1.2.2. *Calorimeters*

The CDF calorimeter system is used to measure the energy of charged and neutral particles and can identify and measure photons, jets from partons, missing transverse energy, and in combination with information from other systems electron and tau leptons. They are arranged around the outer edges of the central tracking volume and solenoid and consist of modular sampling scintillator calorimeters with a tower-based projective geometry. The inner electromagnetic sections of each tower

consist of lead sheets interspersed with scintillator, and the outer hadronic sections are composed of scintillator sandwiched between sheets of steel. The CDF calorimeter consists of two sections: a central barrel calorimeter and forward end plug calorimeters covering the pseudorapidity region $|\eta| < 3.6$.

The D0 liquid-argon calorimeter system is used for the identification and energy measurement of electrons, photons, and jets, and also allows for the measurement of the missing transverse energy ($\not\!\!E_T$) of the events, typically from undetected neutrinos. It is located outside of the tracking and solenoid systems. The central calorimeter (CC) covers detector pseudorapidities $|\eta| \leq 1.1$ and two additional end-cap calorimeters extend the range up to $|\eta| = 4.2$. These fine-grained calorimeters are subdivided into electromagnetic (EM) followed by fine hadronic and then coarse hadronic sections. The intercryostat plastic scintillator detectors complete the calorimeter coverage in the intermediate pseudorapidity region $0.8 < |\eta| < 1.4$.

1.2.3. *Muon detectors*

The CDF muon detector is made up of four independent detector systems outside the calorimeter modules and consists of drift chambers interspersed with steel layers to absorb hadrons. The central muon detector (CMU) is mounted directly around the outer edge of the central calorimeter module and detects muons in the pseudorapidity region $|\eta| < 0.6$. The central muon extension is composed of spherical sections and extends the pseudorapidity coverage in the range $0.6 < |\eta| < 1.0$. The central muon upgrade (CMP) surrounds portions of the CMU and central muon extension (CMX) systems covering gaps in angular coverage and allowing excellent identification of higher momentum muons due to additional layers of steel absorber. The barrel muon upgrade (BMU) is a barrel shaped extension of the muon system in the pseudorapidity region $1.0 < |\eta| < 1.5$. The CMX, CMP and BMU systems also include matching scintillator systems which provide timing information to help identify collision produced muons.

The D0 muon detector system consists of a central muon detector system covering the range $|\eta| < 1$ and forward muon systems which cover the region $1 < |\eta| < 2$. Both central and forward systems consist of a layer of drift tubes and scintillators inside toroidal magnets and two similar layers outside the toroids. Scintillation counters are included for triggering purposes and the 1.8 T toroidal iron magnets make it possible to determine muon momenta and perform tracking measurements within the muon system alone, although in general the central tracking information is also used for muon reconstruction.

The D0 tracking system benefits from a unique feature among high energy collider detectors, namely the ability to reverse regularly (typically every two weeks) the polarities of the solenoid and of the toroid magnets, providing data in four polarity combinations. This allows for a significant reduction of experimental systematic uncertainties related to charged particle properties and for measurements achieving excellent precision, for instance the measurement of inclusive like-sign dimuon

asymmetry described in the heavy-flavor physics chapter.

1.2.4. *Triggering systems*

The CDF trigger system consists of three levels. The level one trigger consists of dedicated electronics that operate at the beam crossing frequency. This system can identify and measure the transverse momentum of charged particles using COT information which provides the basis of several trigger decision criteria. This information is also combined with information from the calorimeters or muon systems to provide a trigger for leptons. The calorimeter trigger hardware measures energy clusters which are used to identify jets and photons as well as an imbalance in event transverse energy interpreted as $\not\!\!E_T$. The second-level trigger operates with a mixture of hardware and software algorithms. It refines the measurements made by the level one trigger and uses broader combinations of information from different subsystems. It adds precision tracking information from the silicon detectors to the fast COT tracks to form trigger decisions sensitive to the presnce of displaced vertices.

The D0 trigger system also has three trigger levels referred to as L1, L2 and L3. Each consecutive level receives a lower rate of events for further examination. The L1 hardware based elements of the triggers used in the electron channel typically require calorimeter energy signatures consistent with an electron. This is expanded at L2 and L3 to include trigger algorithms for instance requiring an electromagnetic object together with at least one jet for which the L1 requirement is calorimeter energy depositions consistent with high-p_T jets. For some inclusive muon samples, events are triggered using the logical `OR` of the full list of available triggers of the D0 experiment. The muon trigger pseudorapidity coverage is restricted to $|\eta| < 1.6$ where the majority of $W\mu\nu$+jet events ($\simeq$65%) are collected by triggers requiring high-p_T muons at L1. Events not selected by the high-p_T muon triggers are primarily collected by jet triggers.

1.3. *Physics object identification at the Tevatron*

1.3.1. *Lepton and photon identification*

Isolated electrons and photons are reconstructed in the calorimeter and are selected in the pseudorapidity regions $|\eta| < 1.1$ at CDF, and at $|\eta| < 1.1$ and $1.5 < |\eta| < 2.5$ at D0.[13] The EM showers are required to pass spatial distribution requirements consistent with those expected from electrons for each section of the calorimeter, and D0 benefits in this respect from the fine longitudinal segmentation of its calorimeter. For electron identification, in CDF a matching track is required within the coverage of the COT tracker, while in the D0 CC region, a reconstructed track, isolated from other tracks, is also required to be matched to the EM shower.

Muons are selected by requiring a local track spanning all layers of the muon detector system (for D0 both within as well as outside of the toroidal magnet). A spatial match is then required to a corresponding track in the COT (CDF) or

CFT (D0).[14] To suppress muon background events originating from the semileptonic decay of hadrons, muon candidate tracks are required to be separated from jets by at least $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\varphi)^2} > 0.5$. A veto against cosmic ray muons is also applied using scintillator timing information in D0 and a specialized tracking algorithm is used both at CDF and D0 to track cosmic ray muons passing through both sides of the detector. Muons can also be identified as a minimum ionizing isolated track in CDF for regions without muon coverage taking advantage of the fact that muons interact with low probability in the material of the calorimeter leaving only a small ionization signature.

Multivariate algorithms are used to enhance efficiency and background rejection in some electrons- and muon-based analysis.

Tau lepton decays into hadrons are characterized as narrow, isolated jets with lower track multiplicities than jets originating from quarks and gluons. Three types of tau lepton decays are distinguished by their detector signature. The type-1 category comprises one-track tau decays consisting of energy deposited in the hadronic calorimeter associated with a single track; type-2 corresponds to one-track tau decays with energy deposited in both the hadronic and EM calorimeters; type-3 are multitrack decays with energy in the calorimeter and two or more associated tracks with invariant mass below 1.7 GeV. In D0, a set of artificial neural networks (NN), one for each tau type, is applied to discriminate hadronic tau decays from jets. The input variables are related to isolation and shower shapes, and exploit correlations between calorimeter energy deposits and tracks. When requiring the neural network discriminants to be above thresholds optimized for each tau type separately, typically 65% of taus are retained, while 98% of the multijet (MJ) background is rejected in the kinematic phase space of the analyses. In CDF boosted decision tree based algorithms are used for the same purpose.

1.3.2. *Jets, b and c jets, and missing transverse energy*

Jets are reconstructed in the calorimeters both at CDF and D0. In CDF, for QCD physics, jets are generally reconstructed with a mid-point cone jet algorithm with a cone of size $\Delta R < 0.7$. Otherwise, jets are reconstructed using a calorimeter based clustering algorithm, with a cone of size $\Delta R < 0.4$. In D0, jets are reconstructed for $|\eta| < 3.2$ using the D0 Run II mid-point cone algorithm.[15] Calorimeter energy deposits within a cone of size $\Delta R < 0.7$ are used to form the jets in QCD physics measurements, otherwise a cone of size 0.5 is used. The energy of the jets is calibrated by applying a jet energy scale correction determined using γ+jet and Z+jet events.[15,16]

Jet identification efficiency and jet resolutions are adjusted in the simulation to match those measured in data.

At both CDF and D0, the identification of quarks initiated by a b or c quark ("b or c tagging") is done in two steps.[17,18] The jets are first required to pass the taggability requirement based on charged particle tracking and vertexing informa-

tion, to ensure that they originate from the interaction vertex and that they contain charged tracks. At CDF the next step in b tagging is done using a NN with similar variables but including additional track quality information.[19] The CDF experiment also employs a cut based secondary vertex tagger.At D0 a b tagging NN is applied to the taggable jets. This NN uses a combination of seven input variables, five of which contain secondary vertex information; the number and mass of vertices, the number of and χ^2 of the vertex contributing tracks, and the decay length significance in the $x-y$ plane. Two impact parameter based variables are also used. As an example at D0 the typical efficiency for identifying a $p_T = 50$ GeV jet that contains a b hadron is $(59 \pm 1)\%$ at a corresponding misidentification rate of 1.5% for light parton (u, d, s, g) initiated jets. This operating point is typically used for events with two "loose" b-tagged jets. When tightening the identification requirement, the efficiency for identifying a jet with p_T of 50 GeV that contains a b hadron is $(48 \pm 1)\%$ with a misidentification rate of 0.5% for light parton jets. Additional requirements are put for c jet identification, and these are typically analysis dependent so are not described here. Typical final identification efficiency for c jets are around 20%, for a misidentification rate of a few %.

The event missing transverse energy ($\not\!\!E_T$)is calculated from individual calorimeter cell energies in the calorimeter. It is corrected for the presence in the event of any muons and all energy corrections to EM objects or to the jets are propagated to $\not\!\!E_T$. Both experiments identify events with instrumental $\not\!\!E_T$ by comparing missing transverse energy calculations based on either reconstructed tracks or calorimeter deposits. The CDF experiment also employs an algorithm that combines tracking and calorimeter information to improve $\not\!\!E_T$ resolution.

On the arXiv, the following chapters, Quantum Chromodynamics Studies, Heavy Flavor physics, Electroweak Physics,Top Quark Physics,Higgs Boson Physics, and Searches for New Particles and New Interactions, are posted as separate arXiv submissions

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2. Quantum Chromodynamics Studies at the Tevatron

2.1. ***Run I results***

2.2. ***Jet final states***

2.3. ***Photon final states***

2.4. ***W/Z+jets final states***

2.5. ***Soft QCD***

3. Heavy Flavor physics at the Tevatron

3.1. ***Characteristics of Flavor Physics at the Tevatron and Run I Results***

3.2. ***Production***

3.3. ***Spectroscopy***

3.4. ***Decays/Lifetimes***

3.5. ***Mixing and Oscillations of Heavy Neutral Mesons***

3.6. ***CP Violation (CPV)***

3.7. ***Rare Decays***

4. Electroweak Physics at the Tevatron

4.1. ***Run I Results***

4.2. ***Physics of the W and Z vector bosons***

4.3. ***Precision Electroweak Measurements on the W boson***

4.4. ***Diboson Production at the Tevatron***

5. Top Quark Physics at the Tevatron

5.1. ***The Top Quark in Run I***

5.2. ***Studies of Top Quark Pair Production***

5.3. ***Observation and Studies of Single Top Quark Production***

5.4. ***Top Quark Mass***

5.5. ***Top Quark Properties***

6. Higgs Boson Physics at the Tevatron

6.1. ***Higgs Boson Theory and Phenomenology***

6.2. ***Analysis Tools***

6.3. ***Searches for the Standard Model Higgs Boson***

6.4. ***Searches for Higgs Bosons Beyond the Standard Model***

7. Searches for New Particles and Interactions at the Tevatron

7.1. ***Theoretical Motivation***

7.2. ***Run I Results***

7.3. ***Supersymmetry***

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