Experiments at the Tevatron from the Discovery of the Top Quark to Search for the Higgs Boson

Outline
- Tevatron program goals
- The Tevatron
- Detectors and data
- Highlights of the recent Tevatron results
- Standard Model Higgs
- Future Tevatron program
- Summary

Disclaimer: DØ is used for majority of the examples, CDF in most cases has similar results

Jefferson Lab Seminar
March 25, 2011
Dmitri Denisov, Fermilab
The Standard Model is the modern theory of particles and interactions:
- Describes majority of phenomena in Nature
- Makes everything of a small number of objects
  - Quarks and leptons
- Forces are carried by
  - photon - electromagnetic
  - gluons - strong
  - W/ Z bosons - weak
- Accurate to a very high precision
  - Better than $10^{-10}$
- Three basic blocks have been discovered at Fermilab
  - B quark
  - Top quark
  - $\tau$ neutrino

But the Standard Model is incomplete:
- Can’t explain observed number of quarks/ leptons, dark energy/ matter
- Model parameters can’t be predicted
- Mechanism for particles to acquire masses is not (yet) understood

Nothing is “wrong” with the Standard Model:
- The goal is to define limits of applicability and find what lies beyond

Dmitri Denisov, Jefferson Lab, 03/25/11
Tevatron Physics Goals

- Precision tests of the Standard Model
  - Weak bosons, top quark, QCD, B-physics...
- Search for particles and forces beyond those known
  - Higgs, supersymmetry, extra dimensions...

Fundamental Questions

- Quark sub-structure?
- Origin of mass?
- Matter-antimatter asymmetry?
- What is cosmic dark matter?
  - SUSY?
- What is space-time structure?
  - Extra dimensions?...
Tevatron: Proton-antiproton Collider

- Chain of six accelerators to get to 1 TeV per beam energy
- Single magnet ring - protons and antiprotons circulate in the opposite directions
- Beam particles wavelength of $\sim 10^{-16}\text{ cm}$
- Objects with mass up to $\sim 2\text{ TeV}$ could be created

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Colliding protons and anti-protons with 1.96 TeV center of mass energy

Energy and luminosity

\[ N_{\text{events}} = \sigma(E) \times L \]

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Bunches in Turn</td>
<td>6 x 6</td>
<td>36 x 36</td>
<td>36 x 36</td>
</tr>
<tr>
<td>( \sqrt{s} ) (TeV)</td>
<td>1.8</td>
<td>1.96</td>
<td>1.96</td>
</tr>
<tr>
<td>Typical L (cm(^{-2})s(^{-1}))</td>
<td>1.6 x 10(^{30})</td>
<td>9 x 10(^{31})</td>
<td>3 x 10(^{32})</td>
</tr>
<tr>
<td>( \int L dt ) (pb(^{-1}/week))</td>
<td>3</td>
<td>17</td>
<td>50</td>
</tr>
<tr>
<td>Bunch crossing (ns)</td>
<td>3500</td>
<td>396</td>
<td>396</td>
</tr>
<tr>
<td>Interactions/crossing</td>
<td>2.5</td>
<td>2.3</td>
<td>8</td>
</tr>
</tbody>
</table>

Run I \( \rightarrow \) Run IIa \( \rightarrow \) Run IIb

0.1 fb\(^{-1}\) \( \rightarrow \) \( \sim \) 1 fb\(^{-1}\) \( \rightarrow \) \( \sim \) 12 fb\(^{-1}\)

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Driven by physics goals detectors are becoming “similar”: silicon, central magnetic field, hermetic calorimetry and muon systems.
Why two detectors?
To verify results, to increase accuracy and chances to discover new phenomena, and to create healthy competition
Silicon Microstrip Tracker

5 barrel layers
800k channels
~10 μm precision

Detector is working well
Stable number of operating sensors

~10 years of radiation aging monitoring provides in depth understanding of complex radiation damage processes

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Scintillating Fiber Tracker

- 8 fibers double layers, 1mm in diameter
- Visible Light Photon Counters (VLPC) readout
  - Light yield of ~7 photo electrons per charged particle
- ~77,000 channels

Fiber tracker and silicon detector are in 1.9T magnetic field created by superconducting solenoid

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**Calorimeter and Muon System**

- **Uranium Liquid Argon calorimeter**
- Drift tubes and scintillation counters based muon system
- ~50,000 channels in each system

Muons are excellent for studies of resonances production

\[ Z \rightarrow e^+e^- \]

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"Dmitri Denisov, Jefferson Lab, 03/25/11"
### Triggering

Rate of interactions between protons and anti-protons is \(\sim 10\) MHz

Only \(\sim 200\) events per second could be written to tapes

Select them with 3 level trigger system very quickly marking interesting events such as with possible Higgs production and decay

**Typical Tevatron store with starting luminosity of** \(3.5 \cdot 10^{32}\) cm\(^{-2}\)sec\(^{-1}\)**
Detectable Objects - Particle Identification

**Final decay products**
- electrons
- muons
- charged tracks
- jets (and b-jets)
- missing $E_T(\nu)$

**Excellent understanding of particles detection**

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**CDF II preliminary**

$Z \rightarrow ee$

$M_Z = (91190 \pm 67_{\text{stat}}) \text{ MeV}$

$\chi^2$/dof = 34/38

**Electrons**

**b-tagging**
Example: Discovery of the Top Quark

Mass of a parent object reconstructed from the decay products

Candidate top quark pair production event display

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Data Collection

- Smoothly recording physics data
- Typical week $\sim 55$ pb$^{-1}$
- On average 92% data taking efficiency
- As of today DØ has $\sim 9.5$ fb$^{-1}$ on tapes

Preliminary Results

Many results published

Most results published

Daily Data Taking Efficiency

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CDF and DØ Collaborations

Behind all technical complexity there are 100’s scientists from all over the world working closely together

CDF: ~540 physicists, 15 countries, 63 institutions

DØ: ~500 physicists, 20 countries, 87 institutions
Use quarks and gluons scattering to study strong interaction
• Rutherford style experiment
• Quarks sub-structure?

Inclusive jet cross sections

1 TeV energy deposition!
Half of the total beams energy

• Measured in the widest kinematic region
  • In rapidity and transverse momentum
• 8+ orders of magnitude $\sigma$ changes
• In agreement with theory predictions

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And More Jets

- High mass di-jet resonances predicted in beyond SM theories
- Masses up to 1.2 TeV studied

CDF Run II Preliminary

No W' observed for now...

\[ \frac{d\sigma}{dM_{jj}} \text{[pb/(GeV/c^2)]} \]

\[ M_{jj} \text{[GeV/c^2]} \]

\[ \alpha_s(p_T) \text{ from inclusive jet cross section in hadron-induced processes} \]

- Determination of the strong coupling constant from the inclusive jet cross sections
- High accuracy \( \alpha_s \) measurement and running of \( \alpha_s \) vs energy studied

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Top Quark Studies

Heaviest known elementary particle:
\[ \sim 173 \text{ GeV} \]

- Measure properties of the least known quark
  - mass, charge, decay modes, etc.
  - data sets of 1000’s of top quarks exist

- Short life time: probe bare quark

Discovery in 1995

1995, CDF and DØ experiments, Fermilab

Today

- Production Cross Section
- Resonance production?
- Production kinematics
- Decay modes
- Branching ratios
- CKM matrix element |V_{tb}|
- Rare decays \( t \rightarrow Zc/\gamma c , \ t \rightarrow WZb \ldots \)
- Non-SM decays \( t \rightarrow H^+ , \ t \rightarrow \tilde{t} \ldots \)
Top Quark Mass Measurement

- Top quark mass is measured using decay products in many different channels
- Lepton+jets channel with two jets coming from W boson is most precise

**Mass of the Top Quark**

<table>
<thead>
<tr>
<th>July 2010</th>
<th>(* preliminary)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDF-I dilepton</td>
<td>167.4 ± 11.4 (±10.3 ± 4.9)</td>
</tr>
<tr>
<td>DØ-I dilepton</td>
<td>168.4 ± 12.8 (±12.3 ± 3.6)</td>
</tr>
<tr>
<td>CDF-II dilepton</td>
<td>170.8 ± 3.8 (± 2.2 ± 3.1)</td>
</tr>
<tr>
<td>DØ-II dilepton</td>
<td>174.7 ± 3.8 (± 2.9 ± 2.4)</td>
</tr>
<tr>
<td>CDF-I lepton+jets</td>
<td>176.1 ± 7.4 (± 5.1 ± 0.3)</td>
</tr>
<tr>
<td>DØ-I lepton+jets</td>
<td>180.1 ± 5.3 (± 5.9 ± 3.6)</td>
</tr>
<tr>
<td>CDF-II lepton+jets</td>
<td>173.0 ± 1.3 (± 0.7 ± 1.1)</td>
</tr>
<tr>
<td>DØ-II lepton+jets</td>
<td>173.7 ± 1.8 (± 0.8 ± 1.6)</td>
</tr>
<tr>
<td>CDF-I alljets</td>
<td>186.0 ± 11.5 (±10.0 ± 5.7)</td>
</tr>
<tr>
<td>CDF-II alljets</td>
<td>174.8 ± 2.5 (± 1.7 ± 1.9)</td>
</tr>
<tr>
<td>CDF-II track</td>
<td>175.3 ± 6.9 (± 6.2 ± 3.0)</td>
</tr>
<tr>
<td>Tevatron combination</td>
<td>173.3 ± 1.1 (± 0.6 ± 0.9)</td>
</tr>
</tbody>
</table>

$\chi^2/\text{dof} = 6.1/10$ (81%)

**DØ and CDF combined top mass result**

$m_t = 173.3 \pm 1.1$ GeV

0.6% accuracy

Best (of any) quark mass measurement!

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**First measurement of quark/anti-quark mass difference: CPT test in quark sector**

$\Delta M = 0.8 \pm 1.8$ (stat.) $\pm 0.8$ (syst.) GeV
Main Top Quark Properties Measured at the Tevatron

- Top quark mass: $m_t = 173.3 \pm 1.1$ GeV (0.6% accuracy)
- Are top and antitop masses the same? Test of CPT
  - $\Delta m = 0.8 \pm 1.9$ GeV (equal to 1%)
- Top quark lifetime
  - $\Gamma_t = 1.99 (+0.69/-0.55)$ GeV agrees with SM
- Top charge $|q| = 2/3e$ to 95% C.L.
- W helicity in top decay expect 70% longitudinal, 30% left-handed
  - SM looks good
- Asymmetry of top quark in $p$ vs $p\bar{p}$ direction expected to be $\sim 1$
  - DZero 8%4%; CDF high mass anomaly?
- Correlations of spins of top and anti-top are consistent with SM
- No flavor changing neutral currents
  - $<2 \times 10^{-4} (t \to gu); <4 \times 10^{-3} (t \to gc)$
- No evidence for SUSY $H^\pm$ in top decays
- Anomalous top vector/ tensor couplings?
  - Combination of W helicity & single top is in good agreement with SM V-A
- 4th generation $t'$? None below $\sim 358$ GeV
- $tt$ resonances? None below $\sim 700$ GeV
- Is W in t decay color singlet? Singlet preferred
- Electroweak single top quark production observed: $|V_{tb}| > 0.77$ @ 95% C.L.

Very well know quark by now!
Electroweak Physics

Precision measurements of electroweak parameters
Measure single and multi-boson production, W mass, W production asymmetry, ...

World most precise W mass measurement

\[
\text{Data} \quad \text{FAST MC} \quad \text{Background} \\
\chi^2/\text{dof} = 48/49
\]

(a) D0, 1 fb^{-1}

\[
\begin{aligned}
\text{Events/0.5 GeV} & \quad 10000 & \quad 7500 & \quad 5000 & \quad 2500 \\
\chi & \quad 50 & \quad 60 & \quad 70 & \quad 80 & \quad 90 & \quad 100 \\
m_T (GeV) & \\
\end{aligned}
\]

80,401 ± 21(stat.) ± 38(syst.) MeV
0.05%

W mass world average is now
80,399 ± 23 MeV (0.025%)
Helps to predict Higgs mass

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Studies of di-boson Production

Detect very rare processes, search for anomalous vector boson couplings and develop experimental methods for Higgs hunting

ZZ has the smallest di-boson cross section
\[ \sigma(ZZ) = 1.6 \pm 0.1 \text{ pb} \]
... next lower is the Higgs

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b-quark Studies

High b quark cross section: $\sim 10^{-3} \, \sigma_{\text{tot}}$
$\sim 10^4$ b’s per second produced!
All b containing species are produced $B^\pm, B^0, B_s, B_c, \Lambda_b…$

Large b quark data samples provide
- B mesons lifetime studies
- Mass spectroscopy ($B_c$, etc.)
- Studies of $B_s$ oscillations
- CP violation studies
- Search for new b hadrons
- Search for rear decays

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New Particles with b-quarks

All b quark containing species are produced: $B^\pm, B^0, B_s, B_c, \Lambda_b$ ...

First baryon with quarks from all three generations observed!

- Until Tevatron, ground state $\Lambda_b$ was the only directly observed $b$ baryon

$\Lambda_b^0 = |bud\rangle$ LEP, DØ, CDF

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**DØ di-muon Charge Asymmetry Puzzle**

- **Di-muon charge asymmetry**
  \[ A_{sl}^{b} = \frac{N_{b}^{++} - N_{b}^{--}}{N_{b}^{++} + N_{b}^{--}} \]
  for events coming from decays of mesons containing b quarks undergoing mixing

- **Standard Model predicts this asymmetry to be very small**
  \[ A_{sl}^{b} = (-2.3^{+0.5}_{-0.6}) \times 10^{-4} \]

- **Any substantial deviation of this asymmetry from zero will be indication of new source of CP violation**

- **Measured value is 3.2σ from prediction**
  \[ A_{sl}^{b} = (-0.957 \pm 0.251 \text{ (stat)} \pm 0.146 \text{ (syst)}) \%

This result might help to understand matter-antimatter asymmetry of the Universe
One of the most exciting studies is to look for new phenomena at the high energy collider SUSY, leptoquarks, technicolor, new exotic particles, extra dimensions...

Example: heavy W' boson search

Check prediction of SM processes in low mass region

Then look into high mass region

Reaching masses of \(~1\)TeV - \(\frac{1}{2}\) of the Tevatron center of mass energy
SUSY Searches

Search for sbottom quarks

No indication of SUSY with particles masses below ~250-400 GeV
Introducing the Higgs

- Mass is a fundamental parameter of any object
  - Inertia, gravitational force, energy
- The fundamental forces of the Standard Model are symmetric (do not depend) upon mass
  - In order to provide particles with masses the symmetry breaking mechanism has been developed
- The “Higgs mechanism” provides mathematical description of mass via “Higgs field”
  - The whole Universe is filled with “Higgs Field”
  - Particles acquire mass by interacting with this field
- The Higgs mechanism predicts existence of new fundamental particle
  - The Higgs particle

It is challenge for experimental physicists to find Higgs particle - the last undiscovered particle of the Standard Model
What is Higgs Mass?

Available experimental limits

→ Direct searches at LEP: $M_H > 114 \text{ GeV}$ at 95% C.L.

→ Precision theory fits

$M_H < 185 \text{ GeV}$ with direct LEP limit

**Light Higgs favored -> in the Tevatron energy range!**

**Tevatron provides:**

**Precision $m_{top}$ and $M_w$ measurements**
Higgs Production and Decays at the Tevatron

Production cross sections
- in the 1 pb range for gg → H
- in the 0.1 pb range for associated vector boson production

Decays
- bb for MH < 130 GeV
- WW for MH > 130 GeV

Search strategy:
- MH <130 GeV associated production and bb decay W(Z)H → lν(ll/νν) bb
  Backgrounds: top, Wbb, Zbb...
- MH >130 GeV gg → H production with decay to WW
  Backgrounds: electroweak WW production...
Experimental Challenges

- Probability of producing Higgs is low
  \[ N_{\text{events}} = L \times \sigma \]
  L is "Tevatron luminosity", \( \sigma \) is "cross section"
- To increase number of produced Higgs bosons we need luminosity

- Backgrounds from Standard Model processes are high
  - Only one out of \( 10^{12} \) collisions might contain Higgs particle
- Separation of backgrounds is one of the main challenges in hunt for the Higgs
Higgs Search: $WH \rightarrow l\nu bb$ ($M_H < 130$ GeV)

- One of the most sensitive channels in the ~110-130 GeV mass range
- Select events with lepton (muon or electron), neutrino (missing energy) and pair of jets from b-quarks
- Dijet mass $\rightarrow$ any peaks?
- For more sensitivity and to use all information about particles in an event
  - Dijet mass $\rightarrow$ multivariate discriminant
Higgs Search: $H \rightarrow WW \rightarrow l^+l^- \nu \nu$ ($M_H > 130$ GeV)

Search strategy:
- 2 high $P_T$ leptons and missing $E_T$
- WW pair comes from spin 0 Higgs: leptons prefer to point in the same direction

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Combining Multiple Channels

Similarly, DØ uses 58 sub-channels
Combining Two Experiments... exclusion!

Tevatron Run II Preliminary, $<L> = 5.9 \text{ fb}^{-1}$

158-175 Higgs mass region is excluded at 95% CL
High Mass Higgs Update March 2011

Tevatron Run II Preliminary, $L \leq 8.2$ fb$^{-1}$

95% CL Limit/SM

$\begin{align*}
\text{Expected} & \quad \text{Observed} \\
\pm 1\sigma \text{ Expected} & \quad +2\sigma \text{ Expected} \\
\end{align*}$

Tevatron Exclusion

$\Delta m_H (\text{GeV/c}^2)$

Cumulative Events

$m_H = 165 \text{ GeV/c}^2$

Signal + Background

Background

Tevatron Data

Higgs cross section twice below SM prediction at 165 GeV is excluded

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Combining Direct and Indirect Searches

March 2011 update: Higgs mass is 114-137 GeV - excellent match for the Tevatron!
Tevatron Luminosity Projections

- Projections are based on extrapolations of the current performance
  - Expected end of Tevatron data collection is October 2011
  - We expect ~12 fb\(^{-1}\) delivered by late 2011, with ~10 fb\(^{-1}\) available for analysis
With 10 fb⁻¹ can reach 95% CL exclusion Higgs in full allowed mass range and 3σ sensitivity at low masses
High yields of low mass states, including Higgs, at the Tevatron complement large cross sections of heavy objects at the LHC
Becoming very exciting!
Challenging search at the LHC at low mass and especially in bb decay mode

Main backgrounds cross sections are increasing faster than signal

~30 fb\(^{-1}\) needed at the LHC to probe main Higgs bb decay mode at low mass

5-10 fb\(^{-1}\) needed for H\(\rightarrow\) \(\gamma\gamma\)

~45 pb\(^{-1}\) accumulated in 2010
Tevatron Projections - 10 fb⁻¹

15 MeV error on W boson mass with no changes in the mean value means SM Higgs exclusion with $M_H < 117$ GeV

Many other exciting studies progressing

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Tevatron Potential

Complementarity
- top spin correlations
- high x gluon
- SUSY searches

Legacy
- top mass
- top properties
- W mass

Higgs
- Hints & Excesses
- top asymmetry
- di-muon asymmetry
- CP in $B_s$
Tevatron Highlights: Summary

Tevatron is performing extremely well
→ expect ~12 fb⁻¹ by late 2011

Experiments are collecting and analyzing data smoothly
→ Many discoveries and precision measurements
→ ~100+ studies in progress publishing ~6 papers per month

Interesting hints of deviations from the Standard Model observed
→ di-muon asymmetry in B meson oscillations
→ Data samples analyzed are to increase by 2-5 times

Many legacy measurements are in progress
→ Will be in the textbooks for a long time!
→ Some results from ppbar collider are unique

Higgs boson search is in a very active stage
→ Excluded at 95% CL Higgs with mass 158-175 GeV
→ Proceeding to exclude wider mass range or...

Thank you for the invitation and an opportunity to share with you exciting results and future plans of the Tevatron