Recent Results from CDF

Gabriele Compostella
(INFN and University of Padova)
on behalf of the CDF Collaboration
Very rich and broad physics program, probing a wide range of processes, whose cross sections span ~10 orders of magnitude:

- study of the interactions of quarks and gluons
- heavy flavor physics
- properties of W and Z bosons
- properties of the top quark
- searches for the SM Higgs boson
- direct searches for physics beyond the Standard Model

This talk will focus only on some of the most recent results from CDF...

Check http://www-cdf.fnal.gov/internal/physics/ for more!
The Tevatron Collider

- Circumference 6.28 km
- ppbar collisions at 1.96 TeV
- Run I (1987-1995)
- Run II (since 2001)
- Surpassed design luminosity
- \(~8 \text{ fb}^{-1}\) on tape per experiment

Peak Luminosity

\(~4 \cdot 10^{32} \text{ cm}^{-2}\text{sec}^{-1}\)
CDF Detector

 Multipurpose collider detector
Large international collaboration, 600+ members

- Silicon tracking
- Large radius drift chamber ($r=1.4m$)
- 1.4 T solenoid
- Projective calorimetry ($|\eta| < 3.5$)
- Muon chambers ($|\eta| < 1.0$)
Diphotons

Crucial for $H \rightarrow \gamma \gamma$

- Notoriously difficult to calculate EM radiation from quarks and initial protons
- Various production mechanisms

Selection in 5.4 fb$^{-1}$:
two photons above 17, 15 GeV $|\eta|<1$

Probing strange PDF

- Exploit the lepton charge correlation
- Select events with W decaying leptonically in 4.3 fb⁻¹:
  tight lepton, large MET, 1 jet
- W charge from lepton
- c charge from soft electron in the jet axis

Signal is evinced from an excess of events in which the charge of the lepton from the W boson decay and the charge of the soft lepton are opposite in sign:

\[ N_{\text{obs}} = N_{\text{OS}} - N_{\text{SS}} \]

\[ \sigma_{WC} = \frac{N_{\text{obs}} - N_{\text{bkg}}}{\epsilon \cdot A \cdot \int \mathcal{L}} \]

\[ \sigma(W+\text{single charm}) \cdot BR(W\to lv) = 33.7 \pm 11.4(\text{stat.}) \pm 7.3(\text{syst.}) \text{ pb} \]

\[ \sigma_{\text{NLO}} = 16.5 \pm 4.7 \text{ pb} \]
\[ \beta_s = \arg \left( -\frac{V_{ts} V_{tb}^*}{V_{cs} V_{cb}^*} \right) \approx 0.02 \]

Processes of new physics can add new phase to \( \beta_s \)

Observation of large CP phase \( \Rightarrow \text{sign of new physics!} \)

Key elements of the analysis:

Angular distribution of \( J/\Psi \) and \( \Phi \) mesons to identify CP-odd and CP-even final states

Identify the flavor of the \( B_s^0 \) or anti-\( B_s^0 \) meson at the time of production by means of flavor tagging (no 4-fold ambiguity)

Unbinned maximum likelihood fit to extract \( \beta_s - \Delta \Gamma = \Gamma_H - \Gamma_L \)

\( B_s^0 \rightarrow J/\Psi (\rightarrow \mu^+ \mu^-) \Phi (\rightarrow K^+ K^-) \) reconstruction (ANN)

\( B_s^0 \rightarrow J/\Psi \rightarrow \mu^+ \mu^- \) and \( \Phi \rightarrow K^+ K^- \) normalized to 5.2 fb
Results updated to $5.2 \text{ fb}^{-1}$

$$\tau_s = 1.53 \pm 0.025 \text{ (stat.)} \pm 0.012 \text{ (syst.)} \text{ ps}$$

$$\Delta \Gamma = 0.075 \pm 0.035 \text{ (stat.)} \pm 0.01 \text{ (syst.)} \text{ ps}^{-1}$$

$$|A_\parallel(0)|^2 = 0.231 \pm 0.014 \text{ (stat)} \pm 0.015 \text{ (syst.)}$$

$$|A_0(0)|^2 = 0.524 \pm 0.013 \text{ (stat)} \pm 0.015 \text{ (syst.)}$$

$$\phi_\perp = 2.95 \pm 0.64 \text{ (stat)} \pm 0.07 \text{ (syst.)}$$

68% and 95% confidence regions in the $(\beta_\Sigma, \Delta \Gamma)$ plane

World’s most precise single measurement of $B_s$ lifetime and decay width difference
Evidence (>3.8σ) of a new structure $Y(4140)$ was found @CDF using $2.7 \text{ fb}^{-1}$

$Y(4140) \rightarrow J/\psi \phi$ through exclusive $B^+ \rightarrow Y(4140)K^+$ decay (PRL 102, 242002)

$Y(4140)$ significance >5σ with the same cuts as before using $5.0 \text{ fb}^{-1}$ data

Suggestive evidence emerging for another structure at 4270 MeV/c²
Lepton + jets sample with $4.8 \text{ fb}^{-1}$
- matrix-element based measurement
- neural network for background discrimination
- in situ $W \rightarrow jj$ jet energy scale (JES) calibration

Precision of this measurement is comparable with 2009 Tevatron combination!

$$M_{\text{top}} = 172.8 \pm 0.7 \text{ (stat)} \pm 0.6 \text{ (JES)} \pm 0.8 \text{ (syst)} \text{ GeV/c}^2 = 172.8 \pm 1.3 \text{ (total) GeV/c}^2$$
# 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>170.6 ± 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 ± 5.3)</td>
</tr>
<tr>
<td>DØ-I lepton+jets</td>
<td>180.1 ± 5.3 (±3.9 ± 3.6)</td>
</tr>
<tr>
<td>CDF-II lepton+jets *</td>
<td>173.0 ± 1.2 (±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>

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

**Top Mass combination**

[M\_top = 173.3±1.1 GeV/c^2](http://www-cdf.fnal.gov/physics/new/top/2010/mass/tevcombination_july/)

- Approaching <1 GeV uncertainty
- Way better than simple scaling with √L
- Entering precision era
Mass difference would imply *CPT-violation*

Measured in a sample of 5.6 fb\(^{-1}\) of lepton + jets events

For each event, reconstruct \(\Delta M_{\text{reco}} = M_{\text{top}} - M_{\text{antitop}}\) and fit the distribution to MC templates with different input \(\Delta M_{\text{top}}\)

\[\Delta M_{\text{top}} = -3.3 \pm 1.7 \text{ GeV/c}^2\]
Short lifetime of top quark decay results in large width $\Gamma_{SM} \sim 1.5$ GeV

Deviation from SM could indicate presence of $t \rightarrow bH^+$ etc.

Different width would change top mass line shape → use mass templates from MC

Method uses same technique from top mass analysis

Dominating source of systematic uncertainty becomes jet resolution

Lepton+jets ($4.3$ fb$^{-1}$):
$\Gamma_{top} < 7.6$ GeV at 95% C.L.
Top Antitop Spin correlations


Top spins are correlated only if \textit{top lifetime is short enough}
Spin-spin correlation is observable in the top quark decay products

\[ \kappa = \frac{N(\uparrow \downarrow) + N(\downarrow \uparrow) - N(\uparrow \uparrow) - N(\downarrow \downarrow)}{N(\uparrow \uparrow) + N(\downarrow \downarrow) + N(\uparrow \downarrow) + N(\downarrow \uparrow)} \]

Lepton + jets sample with 4.3 fb\(^{-1}\):
exploit the helicity angles of lepton, d, and b quarks in a simultaneous likelihood fit

\begin{align*}
\text{Opposite spin fraction:} & \quad f_\text{O} = 0.80 \pm 0.25 \text{ (stat)} \pm 0.08 \text{ (syst)} \\
\text{Spin correlation coefficient:} & \quad K = 0.60 \pm 0.50 \text{ (stat)} \pm 0.16 \text{ (syst)}
\end{align*}
Forward Backward Asymmetry

- QCD predicts small asymmetry effect
- Measure $A_{FB}$ in lab frame
- Unfold to parton level using migration matrix

Lepton + jets sample with 5.3 fb$^{-1}$

$A_{lab}: A_{FB} = 0.150 \pm 0.050_{stat} \pm 0.024_{syst}$

$A_{ttbar}: A_{FB} = 0.158 \pm 0.072_{stat} \pm 0.017_{syst}$

Study rapidity dependence using $A_{ttbar}$

$\Delta y<1.0 : A_{FB} = 0.026 \pm 0.104_{stat} \pm 0.055_{syst}$

$\Delta y>1.0 : A_{FB} = 0.611 \pm 0.210_{stat} \pm 0.141_{syst}$

MCFM : $0.039 \pm 0.006 (<1), 0.123 \pm 0.018 (>1)$

The Higgs boson represents the missing piece of the Standard Model

- From indirect constraints and global EWK fits indications of a relatively light Higgs
- Tevatron experiments sensitive to the mass range 100-200 GeV/c^2
- Search strategy driven by the dominant Higgs decay mode:
  - $H \rightarrow b \bar{b}$ for $M_H < 135$ GeV/c^2 (low mass)
  - $H \rightarrow WW$ for $M_H > 135$ GeV/c^2 (high mass)
Precise measurements of the W boson mass and top quark mass allow to predict the mass of the SM Higgs boson.

\[ \Delta M_W \propto \ln M_H \quad \Delta M_W \propto M_{\text{top}}^2 \]

[W boson Mass]

CDF Run 0/I  
80.436 ± 0.081

D0 Run I  
80.478 ± 0.083

CDF Run II  
80.413 ± 0.048

Tevatron 2007  
80.432 ± 0.039

D0 Run II  
80.402 ± 0.043

Tevatron 2009  
80.420 ± 0.031

LEP2 average  
80.376 ± 0.033

World average  
80.399 ± 0.023
Foundamental check of SM, sensitive to new physics

- Search for 4 leptons (eeee, eeμμ, μμμμ) in 4.8 fb⁻¹
- clean, but small branching fraction

- Select lepton pair with Same Flavor and Opposite Charge with
  $76 < M_{ll1} < 106$ GeV and
  $40 < M_{ll2} < 140$ GeV

- Background from $Z(γ)+$jets events with jets misidentified as leptons is estimated directly from data

5.7σ significance, first observation!

$σ(ZZ) = 1.56^{+0.80}_{-0.63} \pm 0.25$ pb

$σ(ZZ) = 1.4 \pm 0.1$ pb (SM)
Use improved lepton ID in 6 fb\(^{-1}\):
- Improved e and mu isolation
- Tight track quality

Measure $WZ$ cross section in $Z\rightarrow ee$ and $Z\rightarrow \mu\mu$, then combine (50 evts), selecting 3 leptons and high MET

Normalize to $Z\rightarrow ll$ cross section and use its NNLO computed value to get $WZ$ measured xsec

$$\frac{\sigma(p\bar{p} \rightarrow WZ)}{\sigma(p\bar{p} \rightarrow Z)} = (5.5 \pm 0.8 \text{ (stat)} \pm 0.5 \text{ (syst)}) \times 10^{-4}$$

$$\sigma(p\bar{p} \rightarrow WZ) = (4.1 \pm 0.6\text{ (stat)} \pm 0.4 \text{ (syst)}) \text{ pb}$$
Anomalous triple gauge Couplings

- Evidence of $Z + \text{photon}$ interactions is evidence of NP
- Measure coupling in $Z \gamma \rightarrow \gamma \gamma \gamma$ channel
  - Photon Et > 100 GeV, MET > 50 Gev, anti-cosmic cuts (timing, etc.)

- Search for (limit) anomalous coupling parameters via binned maximum likelihood
  - Compare photon Et distribution in data w/ predicted distribution (dependent on the assumed coupling)
  - Anomalous couplings $\rightarrow$ excess at high photon Et $\Lambda = 1500 \text{ GeV}$:

<table>
<thead>
<tr>
<th>Parameter $h_3^{\gamma}$</th>
<th>Measured Limit in Data $(-0.017, 0.016)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h_4^{\gamma}$</td>
<td>$(-0.0006, 0.0006)$</td>
</tr>
<tr>
<td>$h_3^{Z}$</td>
<td>$(-0.017, 0.016)$</td>
</tr>
<tr>
<td>$h_4^{Z}$</td>
<td>$(-0.0006, 0.0005)$</td>
</tr>
</tbody>
</table>

World's tightest limits
Low Mass SM Higgs

WH->lvbb with 5.7fb^{-1} (webpage)

- one of the most sensitive channels at low mass
- Combine different b-tagging algorithms
- Use NN to discriminate signal and background

ZH->llbb with 5.7fb^{-1} (webpage)

- NN derived correction to jets
- 2D NN discriminant (ZH vs top-pair, ZH vs Z+jets)

H->ττ with 2.3fb^{-1} (webpage)

- new tau ID based on BDT: 15-20% improvement
- different BDTs trained against different bkgs and combined

95% C.L. Upper limits on H production cross section:

At $M_H = 115$ GeV/c^2:
- Expected: $3.5 \times \sigma(\text{SM})$
- Observed: $4.5 \times \sigma(\text{SM})$

At $M_H = 115$ GeV/c^2:
- Expected: $5.5 \times \sigma(\text{SM})$
- Observed: $6.0 \times \sigma(\text{SM})$

At $M_H = 115$ GeV/c^2:
- Expected: $24.5 \times \sigma(\text{SM})$
- Observed: $27.9 \times \sigma(\text{SM})$
H→WW→lν l′ν′ with up to 5.9 fb⁻¹:
- 2 leptons + missing ET
- most sensitive channel

To improve S/B separation, search is split in subanalyses:
- opposite sign ll' + 0, 1, ≥2 jets
- opposite sign ll' and Mll' < 20 GeV/c²
- same sign ll' + 1 jet
- three lepton channel
- lepton + hadronic tau

ANN and BDT as discriminants

95% C.L. Upper limits on H production cross section:
At M_H = 165 GeV/c²:
- Expected: 1.0 x σ(SM)
- Observed: 1.08 x σ(SM)
H→WW→lν l'ν' with up to 5.9 fb⁻¹:

- 2 leptons + missing ET
- most sensitive channel

To improve S/B separation, search is split in subanalyses:

- opposite sign ll' + 0, 1, ≥2 jets
- opposite sign ll' and M_{ll'} < 20 GeV/c²
- same sign ll' + 1 jet
- three lepton channel
- lepton + hadronic tau

ANN and BDT as discriminants

95% C.L. Upper limits on H production cross section:

- Expected: 1.0 x σ(SM)
- Observed: 1.08 x σ(SM)

Big improvements in the analysis!
CDF Combination

http://www-cdf.fnal.gov/physics/new/hdg//Results_files/results/cdfcombichep2010/

CDF Run II Preliminary, $<L> = 5.6-5.9$ fb$^{-1}$

LEP Excl.

95% CL Limit/SM

WH→WWW
H→tt
ZH→llbb
bb+Met
WH→lvbb
H→WW

CDF separate analysis

CDF combined

CDF Run II Preliminary, $<L> = 5.6-5.9$ fb$^{-1}$

@MH = 115GeV/c^2
Exp. 1.9, Obs. 1.79

LEP Exclusion

95% CL Limit/SM

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

Low mass sensitivity approaching LEP exclusion:

At $M_H = 115$ GeV/c$^2$:
- Expected: $1.45 \times \sigma$(SM)

At $M_H = 105$ GeV/c$^2$:
- Expected: $1.24 \times \sigma$(SM)

95% C.L. exclusion of the mass range $158 < M_H < 175$ GeV/c$^2$
Most probably SM Higgs mass is low

Tevatron could make it!

Extended Tevatron run was highly suggested by PAC and is currently under discussion.
Complementarity of the Tevatron and the LHC

Scientific Opportunity: the Tevatron and the LHC

The press makes much of the competition between CERN's and Fermilab's Tevatron in the search for the Higgs boson. The competitive aspect is real, and probably adds spice to the scientific exploration, but for us such reporting often feels like spilling the entire pepper shaker over a fine meal. The media emphasis on competition obscures the more important subset of our long-standing collaboration in scientific discovery.

A word from the DGs

Our laboratories and communities have worked together for decades. Europeans have contributed greatly to the Tevatron's many successes, including the discovery of the top quark, the discovery of fast oscillations, and...
Resonant top pair production is predicted by several models beyond the SM.
- Top color assisted technicolor with leptophobic Z
- Randall Sundrum KK-gluons

Lepton +jets, 4.8 fb⁻¹:
- Select btagged events
- Evaluate PDF of the ttbar invariant mass using a Matrix Element method
Heavy t' production suggested in 4th generation models, little Higgs, etc..

Search for t' t' events in the Lepton + Jets final state in 4.6 fb$^{-1}$

\[ M(t') > 335 \text{ GeV}/c^2 \text{ at 95\% C.L.} \]
Conclusions

- The Tevatron and the CDF detector are performing very well
- Datasets keep growing on tape: >10 fb\(^{-1}\) are expected by 2011
- The SM is being extensively tested
- Measurements precision scales better than \(\sqrt{L}\)
- Higgs is difficult but not impossible

...Expect more from Run extension ??!!
- Backup -
High-\(p_T\) muon data sample 6.0 fb\(^{-1}\)

Reconstruct the muonic decay of Z selecting events with two opposite sign muons
- \(66 < M(\mu\mu) < 116 \text{ GeV/c}^2\)
- 0.7 cone midpoint Jets with \(ET > 30 \text{ GeV}\) and \(|\eta| < 2.1\)

Good agreement with the NLO pQCD calculations
Hyperon production

\[
\begin{align*}
\mathcal{L} &= 1.4 \text{ nb}^{-1} \\
\Lambda & \text{ Fit to Double Gaussian} \\
\Xi & \text{ Fit to Double Gaussian} \\
\Omega & \text{ Fit to Gaussian}
\end{align*}
\]

\[p_T \text{ differential cross-section of hyperons with } |\eta| < 1\]

In the minimum bias sample:

\[
\begin{align*}
\Lambda^0 & \rightarrow p\pi \\
\Xi^\pm & \rightarrow \Lambda^0\pi^\pm \\
\Omega^\pm & \rightarrow \Lambda^0K^\pm
\end{align*}
\]
Exploit our large sample of triggered $\Lambda_c \to pK\pi$ events to study $\Sigma_c^0$, $\Sigma_c^{++}$, $\Lambda_c^*$ states
Simultaneous analysis incorporating all cross-talk between channels and threshold effects

<table>
<thead>
<tr>
<th>$\Sigma_c(2455)^0$</th>
<th>167.28 ± 0.12</th>
<th>0.11</th>
<th>1.65 ± 0.50</th>
<th>0.3</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Sigma_c(2455)^{++}$</td>
<td>167.44 ± 0.13</td>
<td>0.11</td>
<td>2.34 ± 0.47</td>
<td>0.4</td>
</tr>
<tr>
<td>$\Sigma_c(2520)^0$</td>
<td>232.88 ± 0.46</td>
<td>0.6</td>
<td>12.51 ± 2.28</td>
<td>1.9</td>
</tr>
<tr>
<td>$\Sigma_c(2520)^{++}$</td>
<td>230.73 ± 0.58</td>
<td>0.5</td>
<td>15.03 ± 2.52</td>
<td>2.1</td>
</tr>
<tr>
<td>$\Lambda_c(2595)^+$</td>
<td>305.79 ± 0.24</td>
<td>0.6</td>
<td>2.59 ± 0.56</td>
<td>+2.0-1.3</td>
</tr>
<tr>
<td>$\Lambda_c(2625)^+$</td>
<td>341.65 ± 0.13</td>
<td>0.6</td>
<td>&lt; 0.97 (90% CL)</td>
<td>&lt;1.9</td>
</tr>
</tbody>
</table>

Comparable or improved precision compared to PDG uncertainties (in red)
Lepton + jets sample with 2.7 fb⁻¹
Measure simultaneously ttbar cross section and background normalizations performing a fit of:
• Neural Network based flavor separator output
• Spectrum of the number of jets
Reminder: l’inizio dell’era dell’Higgs è molto recente, con 2 - 5fb⁻¹
High-Mass Dimuon Resonances

First CDF direct exclusion above 1 TeV
PRL 102, 091805 (2009), 2.3 fb$^{-1}$

Now twice the luminosity, matrix element to incorporate muon $p_T$ resolution weighting

CDF Run II Preliminary 4.6 fb$^{-1}$

$M(Z'_\text{SM}) > 1071$ GeV/c$^2$ at 95% C.L.