Top quark physics at CDF

Karolos Potamianos
On behalf of the CDF collaboration

International Europhysics Conference on High Energy Physics
Grenoble, France
July 21, 2011
The top quark

What?

- Discovered in 1995 at Fermilab;
- Mass much larger than any other fermion;
- $L_{\text{Yukawa}} = -\lambda \bar{\psi}_L \Phi \psi_R$, $\lambda = 0.996 \pm 0.006$
  - What is its role in EWSB?
- Only quark that decays before hadronizing:

$$\begin{array}{c}
t \to W^+ + \ell^+ + \nu
\end{array}$$
Why is the top quark so important?

- Its mass constrains the Higgs boson mass range;
- But this constraint strongly depends on other top properties
  - e.g. the cross-section;
- The top sector is expected to be sensitive to many new physics processes;

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![Graph showing the correlation between m_H and m_t with 68% CL confidence intervals for m_W and m_t.](attachment:graph.png)
Pair production decay signatures at CDF

- **Lepton+Jets**
  - Large BR(30%), good S/B ratio
- **Dileptonic**
  - Highest S/B, but lowest BR(5%)

All hadronic

- Highest BR(44%)  
- But very large QCD background

- $E_T +$ jets
  - Lepton+jets and dileptonic decays where $e/\mu$ is not identified;  
  - Large acceptance to $\tau$;  
  - Large QCD background
Top quark physics

Production properties
- $M_{Z'} > 900 \text{ GeV}/c^2$ @ 95% C.L.
- $M_{W'} > 800 \text{ GeV}/c^2$ @ 95% C.L.
- $M_{b'} > 372 \text{ GeV}/c^2$ @ 95% C.L.
- $F_{gg} = 0.07^{+0.15}_{-0.07}$ (stat+sys)
- $A_{fb} = 15 - 40\%$ (parton level)
- Spin correlations: $\kappa = 0.6 \pm 0.5$ (stat) $\pm 0.2$ (sys)

Intrinsic properties
- $M_t = 173.2 \pm 0.9 \text{ GeV}/c^2$
- $M_{t} - M_{\tilde{t}} = -3.3 \pm 1.7 \text{ GeV}/c^2$
- $\Gamma_t < 7.5 \text{ GeV}/c^2$ @ 95% C.L.
- Exclude $q = -4/3$ @ 95% C.L
- $M_{t'} > 335 \text{ GeV}/c^2$ @ 95% C.L
- $\Gamma_{t'} < 7.5 \text{ GeV}/c^2$ @ 95% C.L
- No evidence for scalar top or top + dark matter

Decay properties
- $V_{tb} = 0.91 \pm 0.11$ (exp) $\pm 0.07$ (theory)
- No evidence for charged Higgs
- $f_0 = 0.67 \pm 0.10$ & $f_+ = 0.02 \pm 0.05$
- $B(t \rightarrow Zq) < 3.3\%$ @ 95% C.L.
- $B(t \rightarrow gu) < 0.2\%$ @ 95% C.L.
Top quark physics: production properties

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Dark matter could couple to SM particles, and thus be produced at hadron colliders;

Search for $p\bar{p} \rightarrow t\bar{t} + X\bar{X} \rightarrow b\ell\nu\bar{b}q\bar{q} + X\bar{X}$;

Excluding $m_{T'} < 360$ GeV/$c^2$ for $m_X < 100$ GeV/$c^2$ at 95% C.L.
[New EPS2011] Dark matter with top quarks [5.7fb$^{-1}$]

- Search for $p\bar{p} \rightarrow t\bar{t} + X\bar{X} \rightarrow bq\bar{q}bq\bar{q} + X\bar{X}$ with $5 \leq N_{jets} \leq 10$;

- Missing momentum flow ($\phi_T$, tracker) is complementary to ($\slashed{E}_T$, calorimeter);
  - They are correlated for events with a missing particle, e.g. neutrino;
  - They are either correlated or anti-correlated in case of a mis-measured jet (main bkg.);

- Data-driven QCD model from $\Delta\phi(\slashed{E}_T, \phi_T) > \pi/2$ region;

Excluding $m_T < 400$ GeV/c$^2$ for $m_X \leq 70$ GeV/c$^2$ @ 95% C.L.
Cross-section and top mass measurement in $\tau+jets$;
Probing top properties in a channel possibly sensitive to new physics;
First measurement of the top mass in the $\tau+jets$ channel;
Using neural network to remove dominant QCD background;

$$\sigma(t\bar{t}) = 8.8 \pm 3.3 \text{ (stat)} \pm 2.7 \text{ (syst)} \text{ pb}$$
$$M_t = 172.7 \pm 9.3 \text{ (stat)} \pm 3.7 \text{ (syst)} \text{ GeV/c}^2$$
Top cross-section in lepton+\(b\)-jets \([4.3\text{fb}^{-1}]\)

Counting experiment after background understanding:

- \(W+\text{HF}\) cross section underestimated in the MC: \(W+\text{HF}\) content measured in data in the 1 or 2 jet event sample
- \(b\)-tagging mistag rate measured in data, parametrization applied to \(W+\text{jets}\);
- CDF measures ratio of \(t\bar{t}/Z \rightarrow \ell\ell\) with the same trigger and use the theoretical \(Z\) cross section to remove the uncertainty due to luminosity measurement

\[
\sigma(t\bar{t}) = 7.32 \pm 0.36 \text{ (stat)} \pm 0.59 \text{ (syst)} \pm 0.14 \text{ (Z theory)} \text{ pb}
\]
One step further: signal/background discrimination:

- $t\bar{t}$ more energetic, central and isotropic than $W+\text{jets}$
- NN input variables: $H_T$, aplanarity, sphericity, etc.
- Template fit of $t\bar{t}$ and $W+\text{jets}$ to the discriminant output
- CDF measures ratio of $t\bar{t}/Z \rightarrow \ell\ell$ with the same trigger and use the theoretical $Z$ cross section to remove the uncertainty due to luminosity measurement

PRL 105 012001 (2010)

$\sigma(t\bar{t}) = 7.82 \pm 0.38 \text{ (stat)} \pm 0.37 \text{ (syst)} \pm 0.15 \text{ (Z theory)} \text{ pb}$
Looser event selection, better constraint on backgrounds

- Use events with 1 lepton, $\geq 1$ jet, $\geq 1 b$-tag to measure signal cross section and background contributions;
- Templates: NN based flavor separator, $N_{\text{jets}}, N_{b-\text{tags}}$; 
- Simultaneous in situ fit for $\sigma(t\bar{t})$, $W+HF$ fractions and systematic sources;
- Potentially very sensitive as more data is added;

$$\sigma(t\bar{t}) = 7.64 \pm 0.57 \text{ (stat+syst)} \pm 0.45 \text{ (lumi)} \text{ pb}$$
Top cross-section in dilepton decay [5.1fb^{-1}]

Signal/background discrimination

- $H_T$ and $E_T$-significance cuts, or b-tagging

\[ \sigma(\bar{t}t) = 7.40 \pm 0.58 \text{ (stat)} \pm 0.63 \text{ (syst)} \pm 0.45 \text{ (lumi)} \text{ pb [pre-tag]} \]
\[ \sigma(\bar{t}t) = 7.25 \pm 0.66 \text{ (stat)} \pm 0.47 \text{ (syst)} \pm 0.44 \text{ (lumi)} \text{ pb [tagged]} \]
Top cross-section in $E_T + \text{jets} \ [2.2\text{fb}^{-1}]$

$E_T + \text{jets}$: alternative way to $\tau$ channels, and recover unidentified $e/\mu$

- Independent from lepton+jets channel
- At least 3 strict identified jets, at least one $b$-tagged jet;
- NN trained against background, $NN > 0.8$ background estimation;
- $b$-tag rate/misrate from data in a 3 jet sample (small signal contamination);
- Counting experiment: counts the number of $b$-tagged jet;

$$\sigma(t\bar{t}) = 7.99 \pm 0.54 \ (\text{stat}) \pm 0.76 \ (\text{syst}) \pm 0.46 \ (\text{lumi}) \ \text{pb}$$
Top in $E_T + 2\ b$-jets [5.7fb$^{-1}$]

- Many new particles can appear here
  - Higgs ($ZH \rightarrow \nu \nu b \bar{b}$); SUSY: $\tilde{b} \tilde{b} \rightarrow b \chi^0 \bar{b} \chi^0$;
  - Technicolor: $\rho_T^\pm \rightarrow Z \pi_T^\pm \rightarrow \nu \nu b \bar{q}$; Third generation leptoquarks;
- $\sigma(t\bar{t})$ measurement here is a test of the backgrounds for Higgs and NP;
- Independent from other measurements: can be combined easily;
- Using same strategy as in search for $ZH \rightarrow \nu \nu b \bar{b}$:
  - Suppress overwhelming QCD background using multivariate technique (NN)
  - Isolate the signal from remaining backgrounds, likelihood scan of NN output

$\sigma(t\bar{t}) = 7.11 \pm 0.49 \ (\text{stat}) \pm 0.96 \ (\text{syst}) \pm 0.43 \ (\text{lumi}) \ \text{pb}$
Summary of cross-section measurement at CDF

![Graph showing cross-section measurement results]

This is still the state of the art!
Results are consistent, and the best channel (lepton+jets) is precise to 6.5%: strong constraint on new physics models.
Top quark charge asymmetry: $A_{fb}$ (at the Tevatron)

Any new physics scenario must to contend with precisely measured $t\bar{t}$ properties.

Effect also seen at DZero; More in talks on Saturday;
Top quark physics: decay properties

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First model-independent, simultaneous measurement of $W$ boson helicity exclusively in dilepton channel;

Combination of measurements from untagged and tagged samples;

For pre-tagged events

$K$-S Test : 0.739
$\chi^2$ Test : 0.726

(Entries : 608)

$\ttbar$ ($M_{\text{top}}=175$ GeV)
Diboson
DY $\rightarrow$ ee+$\mu\mu$
DY $\rightarrow$ $\tau\tau$
Fakes

CDF Run II Preliminary (5.1 fb$^{-1}$)

$f_0 = 0.74^{+0.18}_{-0.17}$ (stat) ± 0.06 (syst); $f_+ = -0.09 \pm 0.09$ (stat) ± 0.04 (syst)
Top quark physics: intrinsic properties

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$M_t$ in $t\bar{t} \rightarrow b\bar{b}q\bar{q}q\bar{q}$

- Using b-tagging and multivariate techniques to isolate the signal from the overwhelming QCD background;
- Jet energy scale (JES) is the largest systematic uncertainty;
  - Using $W \rightarrow q\bar{q}$ decays to constrain it in situ;
- Fully reconstruct the kinematics so to reconstruct the top quark mass;

$M_t = 172.5 \pm 1.7 \text{ (stat+JES)} \pm 1.2 \text{ (syst)} \text{ GeV/c}^2$
**Mt in \( \bar{t}t \to b\bar{b}q\bar{q}E_T \)**

- Limited lepton ID mostly due to limited detector coverage;
- But \( \bar{t}t \) has striking kinematics:
  - Still possible to reconstruct one \( W \) and one top in this final state;
- Background modeled from low-end of \( NN \) separating \( \bar{t}t \) from data;

Dijet pair closest to \( W \) mass to measure jet energy scale.  
Reconstruct one of the two decaying top to measure the top quark mass.

\[
Mt = 172.3 \pm 2.4 \text{ (stat+JES)} \pm 1.0 \text{ (syst) GeV/c}^2
\]
Combining over 5,000 top pair events from orthogonal datasets.

\[ M_t = 173.3 \pm 1.1 \text{ GeV}/c^2 = 173.3 \pm 0.6 \text{ (stat)} \pm 0.9 \text{ (syst)} \]

Summer 2011 combination expected soon!!!

Precision of about 1 GeV/c^2!!!
Sixteen years after its discovery, the CDF/Tevatron dataset helped expand our knowledge of the top quark, thanks to extensive measurements of top quark intrinsic properties, study of its production and decay;

With the LHC results, Tevatron will still play an important role:

- Some Tevatron measurements – its mass! – have broad impact to our field, and will be a long standing legacy;
- Others such as charge asymmetry, spin correlations are complementary to the LHC program

Study of forward-backward asymmetry of top events shows discrepancy with current NLO QCD prediction.

- Waiting for NNLO calculation.
- Also, twice the data available to soon confirm or disprove the existing excess!
- More about this in Saturday sessions;

More results and details on our webpage:
http://www-cdf.fnal.gov/physics/new/top/top.html
What about single top?

- Single top was observed in 2009 by both Tevatron experiments;
- CDF used up to 3.2 fb$^{-1}$; Was this updated?
- We are working on an update with more than twice the dataset;
  - Will likely be ready for Lepton-Photon: stay tuned!

CDF Run II Preliminary, $L = 3.2$ fb$^{-1}$

$|V_{tb}| > 0.71$ (95% C.L.)

Single Top Quark Cross Section

<table>
<thead>
<tr>
<th></th>
<th>CDF Lepton+jets 3.2 fb$^{-1}$</th>
<th>CDF MET+jets 2.1 fb$^{-1}$</th>
<th>DØ Lepton+jets 2.3 fb$^{-1}$</th>
<th>Tevatron Combination Preliminary</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$2.17^{+0.56}_{-0.55}$ pb</td>
<td>$5.0^{+2.6}_{-2.3}$ pb</td>
<td>$3.94^{+0.88}_{-0.88}$ pb</td>
<td>$2.76^{+0.58}_{-0.47}$ pb</td>
</tr>
</tbody>
</table>

$m_{t\bar{t}} = 170$ GeV

CDF Run II Preliminary, $L = 3.2$ fb$^{-1}$

Super Discriminant

MJ Discriminant

Events

<table>
<thead>
<tr>
<th></th>
<th>Single Top</th>
<th>W+HF</th>
<th>$t\bar{t}$</th>
<th>QCD+Mistag</th>
<th>Other</th>
<th>Data</th>
</tr>
</thead>
</table>
Backup Slides
Intrinsic $E_T$ vs. instrumental $E_T$

**How we measure $E_T$**

- Typically provided by the transverse energy imbalance ($E_T$) in the calorimeter;
- We also use the transverse momentum flow imbalance ($\rho_T$) from the spectrometer;
  - $\rho_T$ largely correlated with $E_T$ in presence of neutrinos (or $\tilde{\chi}^0$, etc.);
  - Very different for instrumental $E_T$: $\rho_T$ and $E_T$ either correlated or anti-correlated;

**Exemple: $ZZ \rightarrow \nu\nu b\bar{b}$**

$[E_T$ aligned to $\rho_T]$  

$[\rho_T$ is not aligned to $E_T]$  

**Example: QCD $b\bar{b}$**

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