Top Physics at the Tevatron

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On behalf of the CDF and D0 Collaborations

2009 APS April Meeting
Top Physics

• Discovered in 1995 by CDF and D0 ⇒ the first surprise: its large mass
  ▸ is it just an “ordinary” quark?
  ▸ does it have a special role in the EWSB?

• With 50 times more data, we can now study its properties accurately
• Extensive program at the Tevatron

Today overview of top at the Tevatron focus on:
experimental challenges
latest results
Top Production

Tevatron
Proton and anti-protons collisions at 1.96 TeV
center of mass energy

Strong pair production

\[ \sim 85 \% \quad \sim 15 \% \]

\[ \sigma_{NLO} = 6.7 \pm 0.8 \text{ pb} \quad \text{(for } M_t=175\text{GeV}) \]


EWK single-top production

\[ \sigma_{NLO} = 1.98 \pm 0.21 \text{ pb} \quad \sigma_{NLO} = 0.88 \pm 0.07 \text{ pb} \]

(for \( M_t=175\text{GeV} \))

Top Production

QCD pair production

$\sim 85\%$

$\sim 15\%$

$\sigma_{NLO} = 6.7 \pm 0.8 \text{ pb}$

(For $M_t=175\text{GeV}$)

Cacciari et al., JHEP 0809, 127 (2008). Compatible Predictions:

EWK single-top production

$\sigma_{NLO} = 1.98 \pm 0.21 \text{ pb}$

$\sigma_{NLO} = 0.88 \pm 0.07 \text{ pb}$

(for $M_t=175\text{GeV}$)


1 top pair each $10^{10}$ inelastic collisions
Top Decay

t → Wb ~ 100%

Channels defined by the W decay

Top Pairs

Branching ratios

- All-hadronic: 44%
- Lepton + Jets (e and μ): 30%
- Dilepton (e and μ): 21%
- Tauonic: 5%

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Top Signatures

- Hadronic: large BR, many jets: large QCD background
- Lepton + Jets:
  - Signature includes high pt leptons and missing energy
  - jet backgrounds can be largely rejected already at trigger level
- Dileptons: clean signature due to two leptons, but small BR
- All benefit by identification of b-jets
• General Purpose detectors
• Top physics uses almost all their capabilities
Thanks to our colleagues at the accelerator

Data!

more than 6 fb\(^{-1}\) delivered

Today: samples up to 3.6 fb\(^{-1}\), 
L+Jets ~1000 Top events

Thanks to our colleagues at the accelerator
Top Production
Test of QCD predictions

$\Rightarrow 6.7 \text{ pb}, \text{ uncertainty } \sim 10\%$ (1)

(1) @ Mt 175GeV

Could provide hints of New physics:

✧ as it may manifest in different channels:

✓ check consistency across final states

Provides sample composition for other measurements


Compatible Predictions:
Lepton + Jets
Using b-identification

Lepton + jets channel

• Selection based on high pt lepton, missing transverse energy and ≥ 3 jets
• Largest backgrounds W+jets and QCD
  ➡ Exploit presence of b-jets in final state
  increase S/B from 1/4 to 3/2 (~1 b-tag)

- tag efficiency ~50% with <1% mistag

Others methods:
NN, Soft Lepton, Jet Probability
Lepton + Jets
Using b-identification

Lepton + jets channel

- Selection based on high pt lepton, missing transverse energy (MET) and \( \geq 3 \) jets
- Background Estimation:
  - Electroweak: Monte-Carlo based
  - W+jets (mainly Heavy flavor jets) and QCD: derived using data-driven approach

\[ \sigma = 7.1 \pm 0.4 \text{ (stat)} \pm 0.6 \text{ (syst)} \pm 0.4 \text{ (lumi)} \text{ pb} \]

Adding cut on sum of transverse energy
\( HT > 250 \text{ GeV} \)

\[ \Delta \sigma / \sigma = 11.6\% \]

Lepton + Jets
1 fb\(^{-1}\)

\[ \sigma = 7.42 \pm 0.53 \text{ (stat)} \pm 0.46 \text{ (syst)} \pm 0.45 \text{ (lumi)} \text{ pb} \]
Use event kinematics and shapes to distinguish top from background events

feed a Neural Net and build a discriminant

- Systematic do not suffer from b-tagging related uncertainties
- sensitive to signal and background modeling systematics
- reduce QCD: tighten MET and leading Jet $E_T$

$\sigma = 7.1 \pm 0.4 \text{ (stat)} \pm 0.4 \text{ (syst)} \pm 0.4 \text{ (lumi)} \text{ pb}$

$\frac{\Delta \sigma}{\sigma} = 10\%$
Reducing systematic unc.

- Reduce systematic from Luminosity uncertainty by normalizing over the Z cross section

\[ \sigma_{t\bar{t}} = R \cdot \sigma_{Z}^{\text{theory}} \]

- Measured Z cross section on the same samples as used on the top pair cross section

\[ \sigma_Z = 253.27 \pm 1.01 \text{ (stat)} + 4.4 \, -4.6 \text{ (syst)} + 16.63 \, -13.71 \text{ (lumi)} \text{ pb} \]

\[ \text{theory : } \sigma_Z = 251.3 \pm 5.0 \text{ pb } \]  

LJ Topological

\[ \sigma = 6.9 \pm 0.4 \text{ (stat)} \pm 0.4 \text{ (syst)} \pm 0.1 \text{ (theory)} \text{ pb} \]

\[ \Delta \sigma/\sigma = 8.3\% \]

LJ b-tagged

\[ \sigma = 7.0 \pm 0.4 \text{ (stat)} \pm 0.6 \text{ (syst)} \pm 0.1 \text{ (theory)} \text{ pb} \]

\[ \Delta \sigma/\sigma = 10\% \]
Measurements consistent across channels and experiments

New measurements precision is ~8%, comparable with that of the theory

Updating each experiment combination and working on a Tevatron one
Single Top

- Direct measurement of $|V_{tb}|$

- Sensitive to BSM:
  - FCNC
  - $W'$
  - anomalous couplings
  - Charged Higgs

- Benchmark for Higgs searches:
  similar final state as WH

- Not a striking signature as top pair production
- Large Backgrounds
- with Large systematics

Need Multi-Variate techniques

details on Single-Top Mini-symposium

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Single Top

Open the box and.....

On March 4 2009
Reported by both Experiments

5.0 \sigma

Observation

CDF

\( \sigma > 5.9 \sigma \)

D0

4.5 \sigma
Single Top

CDF Preliminary Single Top Summary
For $M_{top} = 175$ GeV/c²

| Source | Cross-Section (pb) | $|V_{tb}|$ |
|--------|-------------------|---------|
| S-Channel | $1.5 \pm 0.9$ | 0.71 @ 95%CL |
| Neural Network | $1.8 \pm 0.6$ | |
| Matrix Element | $2.5 \pm 0.7$ | |
| Likelihood Function | $1.6 \pm 0.8$ | |
| Boosted Decision Tree | $2.1 \pm 0.7$ | |
| Combination (Lepton+Jets) | $2.1 \pm 0.7$ | |
| Combination (MET+Jets) | $4.9 \pm 2.6$ | |
| Combination (All Channels) | $2.3 \pm 0.6$ | |

**CDF**

- $|V_{tb}| > 0.71$ @ 95%CL
- $|V_{tb}| = 0.91 \pm 0.11$ (exp) ± 0.07 (th)

**DØ**

- $|V_{tb}| > 0.78$ @ 95%CL
- $|V_{tb}| = 1.07 \pm 0.12$

**Cross-Section (pb)**

- **CDF**: $2.3^{+0.6}_{-0.5}$ (@ $m_{t} = 175$ GeV)
- **DØ**: $3.94 \pm 0.88$ (@ $m_{t} = 170$ GeV)

**σ ($p\bar{p} \rightarrow tb+X, tqb+X$) [pb]**

- **CDF**: $3.74^{+0.95}_{-0.79}$ pb
- **DØ**: $4.30^{+0.99}_{-1.20}$ pb

- **BLUE Combination**: $4.16 \pm 0.84$ pb
- **BNN Combination**: $3.94 \pm 0.88$ pb

N. Kidonakis, PRD 74, 014012 (2006) $m_{top} = 170$ GeV

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Top Mass
Why measure the top mass?

- fundamental parameter of the SM and a striking feature of the top quark
  - consistency within SM
- Relates to Higgs mass through loop corrections of the W mass
  - indirect constrain on Higgs mass
  - and physics beyond SM
• Measure jets no partons

√ need to correct for detector effects, hadronization and underlying event: Jet Energy Scale (JES) uncertainties ~ 3% (vary with $E_T$) dominant source of systematic

√ assignment jet-partons: combinatoric problem
Challenges

- Measure jets no partons
  - need to correct for detector effects, hadronization and underlying event: Jet Energy Scale (JES) uncertainties ~ 3% (vary with $E_T$) dominant source of systematic
  - assignment jet-partons: combinatoric problem

  reduced by using b-tagging information
**Techniques**

**Matrix Element**

Define an event probability that the observed kinematics arise from a top pair decay as a function of the top mass and JES.

- Integrate over the parton-level differential cross section, PDF and transfer functions that maps a set of observed variables to that of the partons (detector resolution effects).
- Maximize Final Likelihood: product of the Probabilities for the observed data

**Template**

- build distribution (template) of variables sensitive to top mass and JES
- Maximize a likelihood where observed distributions are compared to expectations at different top mass and JES
Lepton+Jets Channel

- 4 jets and $\geq 1$ b-tag
- Matrix element technique
- In-situ JES calibration

$\Delta_{\text{JES}}$: shift in units of JES error

$2D \text{ Likelihood: } L(m_t, \Delta_{\text{JES}})$

172.1 ± 0.9 (stat) ± 1.3 (syst) GeV/c$^2$

single measurement with precision <1%

173.7 ± 0.8 (stat) ± 1.6 (syst) GeV/c$^2$
Dilepton Channel

- matrix element technique
- using $e\mu, \geq 2$ jets

Combine with result from a template method with Neutrino Weighting Algorithm (in 1 fb$^{-1}$)

$\rightarrow$ NWA used to resolve the under-constrained kinematics due to 2 neutrinos.

$174.8 \pm 3.3$ (stat) $\pm 2.6$ (syst) GeV/c$^2$

$174.7 \pm 2.9$ (stat) $\pm 2.4$ (syst) GeV/c$^2$

$\sigma/m_t = 2.2\%$
All-Hadronic Channel

- Very challenging due to large QCD backgrounds
- select events with $\geq 6$ jets, 1 and $\geq 2$ b-tag
- use NeuralNet (including jet shape variables for $q$ vs $g$ initiated jets) to discriminate Signal over Background.
- Includes In-Situ JES calibration
- Template method ($m_t, \Delta_{\text{JES}}$)

$174.8 \pm 1.7 \text{ (stat)} \pm 1.9 \text{ (syst)} \text{ GeV/c}^2$

$\sigma/m_t = 1.5\%$
Reducing JES dependence

Exploit correlation between Lepton momentum and top mass in L+J channel.

Indirect Measurement

Using parametrizations of the experimental and theoretical cross section as a function of mass:

build a joint Likelihood \( L(\sigma, m_t) \)

\[ \text{DØ RunII preliminary (1 fb}^{-1}) \]

- Measured \( \sigma_T \)
- Nadolsky et al., PRD 78, 013004 (2008)
- Cacciari et al., JHEP 09, 127 (2008)
- Moch and Uwer, PRD 78, 034033 (2008)

169.1^{+5.9}_{-5.2} \text{ GeV/c}^2

done for LJ and DIL
NLO+NLL and NNLO\text{approx}


172.1 \pm 7.9 \text{ (stat)} \pm 3.0 \text{ GeV/c}^2

combine electron and muon
checked using mean and shape

2.7 fb^{-1}
Top Mass combination

Most precise measurements per channel and per experiment

• Consistent results between channels

• Combine results for better precision

CDF Top Quark mass (*Preliminary)

- All-hadronic (Run I)
  - 186.0 ± 10.0 ± 5.7

- Dilepton (Run I)
  - 167.4 ± 10.3 ± 4.9

- Lepton+jets (Run I)
  - 176.1 ± 5.1 ± 5.3

- Dilepton (1.9 fb⁻¹)
  - 171.2 ± 2.7 ± 2.9

- Lepton+Jets (Lxy+lepton pₜ)
  - 175.3 ± 6.2 ± 3.0

- Lepton+Jets (3.2 fb⁻¹)
  - 172.1 ± 0.9 ± 1.3

- All-hadronic (2.9 fb⁻¹)
  - 174.8 ± 1.7 ± 1.9

- CDF Winter 09 (3.2 fb⁻¹)
  - 172.6 ± 0.9 ± 1.2 (stat.) ± (syst.)
  - χ²/dof = 3.6/6 (73%)

DØ

- * = preliminary

Run I Dileptons 0.1 fb⁻¹
  - 168.4 ± 12.3 ± 3.6 GeV
  - ± 12.8 GeV

Run I Lepton+jets 0.1 fb⁻¹
  - 180.1 ± 3.6 ± 3.9 GeV
  - ± 5.3 GeV

Run II Dileptons * up to 3.6 fb⁻¹
  - 174.7 ± 2.9 ± 2.4 GeV
  - ± 3.8 GeV

Run II Lepton+jets * 3.6 fb⁻¹
  - 173.7 ± 0.8 ± 1.6 GeV
  - ± 1.8 GeV

DØ combined (March 2009)
  - 174.2 ± 0.9 ± 1.5 GeV
  - ± 1.7 GeV

World average (March 2009)
  - 173.1 ± 0.6 ± 1.1 GeV
  - ± 1.3 GeV

Run II c[(+jets,II,II+)] * 1 fb⁻¹
  - 169.1 ± 5.6 GeV

Winter 2009

150 160 170 180 190 200
Top Quark Mass (GeV)

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Systematic Uncertainties

- Measurements are systematic dominated.
- Part of JES however has became statistical (from In-situ calibration)
- Still residual JES (differences with respect to b-jets JES or dependence on $p_T$ or $\eta$)

On-going joint (CDF+D0) effort to re-examine each source of uncertainty established common categories

<table>
<thead>
<tr>
<th>Systematic source</th>
<th>Systematic uncertainty (GeV/$c^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calibration</td>
<td>0.2</td>
</tr>
<tr>
<td>MC generator</td>
<td>0.5</td>
</tr>
<tr>
<td>ISR and FSR</td>
<td>0.3</td>
</tr>
<tr>
<td>Residual JES</td>
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<tr>
<td>$b$-JES</td>
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<tr>
<td>Lepton $p_T$</td>
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<tr>
<td>Multiple hadron interactions</td>
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</tr>
<tr>
<td>PDFs</td>
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<tr>
<td>Background</td>
<td>0.5</td>
</tr>
<tr>
<td>Color reconnection</td>
<td>0.4</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1.1</strong></td>
</tr>
</tbody>
</table>

Example taken from CDF LJ analysis
Tevatron combination

173.1 ± 0.6 (stat) ± 1.1 (syst)
★ 1.3 GeV/c² uncertainty
★ 0.75% precision

Electroweak fit which incorporates new 
TeV top mass
and the TeV 95%CL exclusion of the SM 
Higgs Boson
(160-170GeV)

From EWK fits
m_H=90 +36 -27 GeV
m_H < 163GeV

Reference:
arXiv:0903.2503

http://lepewwg.web.cern.ch/LEPEWWG/
173.1 ± 0.6 (stat) ± 1.1 (syst)

★ 1.3 GeV/c² uncertainty
★ 0.75% precision

Already beyond RunII goal, can we do even better? on-going studies....

Top Properties

and

Searches for new physics
New Physics may appear only on some channels: for example $t \rightarrow H^+ b \rightarrow \tau \nu b$

Cross-section ratios

$R_{ll/lj} = 0.86^{+0.19}_{-0.17}$

$R_{\tau l/ll+lj} = 0.97^{+0.32}_{-0.29}$

Consistent with SM expectation

Establish limits on $Br(t \rightarrow H^+ b)$

$H^+ \rightarrow \tau \nu, H^+ \rightarrow c\bar{s}$

References:
CDF PRL 96 042003 (2006)
D0 arXiv.org:0903.5525
Resonant Production

- Search for narrow-width resonances decaying into a pair of top quarks
- L+Jets channel (3 or more jets), 1 or more b-tags
- Reconstruct invariant mass and compare with templates built from simulation (for SM contributions and various narrow width heavy resonances).

References: CDF PRL 100 238101 (2008) (~0.7 fb⁻¹, M_{Z'} < 725 GeV)
D0 PLB 668, 98 (2008) (~0.9 fb⁻¹, M_{Z'} < 700 GeV)

for a narrow width topcolor Z'
M_{Z'} < 820 GeV excluded @ 95%CL
Forward-backward asymmetry

- New physics models could give rise to a \( A_{FB} \) asymmetry (axigluons).

- NLO QCD calculations predict: \( A_c = 5 \pm 1.5\% \) (\( p\bar{p} \) frame)

- If CP, it can be interpreted as
  \[
  A_{FB} = \frac{N_t(p) - N_t(\bar{p})}{N_t(p) + N_t(\bar{p})}
  \]

- \( L+\text{Jets} \) channel (\( \geq 4 \) jets), \( \geq 1 \) b-tag

- Use rapidity of hadronically decaying top

- Correct by detector effects

\[ A_{FB} = 19.3 \pm 6.5 \text{ (stat)} \pm 2.4 \text{ (syst)} \% \]

References:
- CDF PRL 100 202001 (2008) : 1.9 fb\(^{-1}\), \( A_{FB} = 0.17 \pm 0.08 \)
- D0 PRL 100, 142002 (2008) : 0.9 fb\(^{-1}\), \( A_{FB} = 0.12 \pm 0.08 \) (observed)
Examining the Wtb vertex

W boson helicity

In SM
\[ t \rightarrow Wb \sim 100\% \]

due to the V-A nature of the vertex, expect:

- Left-Handed: \( f \approx 0.3 \)
- Longitudinal: \( f_0 \approx 0.7 \)
- Right-Handed: Suppressed

Suppressed decay angle of down-type fermion in the W rest frame with respect to the top quark direction

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W Helicity

probing the tWb vertex

Using L+J and Dilepton

compare data to signal+background templates for given fraction values

make 2D fit (model independent)

\[ f_0 = 0.490 \pm 0.106 \text{ (stat)} \pm 0.085 \text{ (syst)} \]
\[ f_+ = 0.110 \pm 0.059 \text{ (stat)} \pm 0.052 \text{ (syst)} \]

1 fb\(^{-1}\) Reference:
D0 PRL 100 062004 (2008)

Reference:
CDF PLB 674 p160 (2009)

Combination

assuming \( f_+ = 0 \)
\[ f_0 = 0.62 \pm 0.10 \text{ (stat)} \pm 0.05 \text{ (syst)} \]

or \( f_0 = 0.7 \)
\[ f_+ = -0.04 \pm 0.04 \text{ (stat)} \pm 0.03 \text{ (syst)} \]
Anomalous Couplings

\[ L_{tWb} = \frac{g}{\sqrt{2}} W_\mu^- b \gamma^\mu \left( f^L_1 P_L + f^R_1 P_R \right) t - \frac{g}{\sqrt{2} M} \partial_\nu W_\mu^- b \sigma^{\mu\nu} \left( f^L_2 P_L + f^R_2 P_R \right) t + h.c. \]

**SM values:** \( f^L_1 = 1, \quad f^R_1 = f^L_2 = f^R_2 = 0 \)

- Observables like the W helicity fractions or the single top cross section will depend on the tWb couplings (C.R. Chen, F. Larios and C.P. Yuan, Phys. Lett. B 631:126)
- Our measurements can therefore be used to do a general analysis of the vertex
- By investigating one pair of coupling form factors at a time (others at SM value):

  - Consistent with SM

  - Find 95% CL if \( f^L_1 = 1 \)
    - \(|f^R_1|^2 < 0.72\)
    - \(|f^L_2|^2 < 0.19\)
    - \(|f^R_2|^2 < 0.20\)

Reference: D0 PRL 102 092002 (2009)
Search for heavy Top-like quarks

- Search for a heavy top-like quark ($t'$) decaying to $Wq$

- Present in various theories
  - predicting 4-th generation of massive fermions PRD 64, 053004 (2001)
  - Fermion doublets: Beautiful Mirrors PRD 65, 053002 (2002)

- In $L+Jets$ channel, reconstruct event and perform a 2D Likelihood fit to $M_t$ and $H_T$

Excluding $t'$ at $95\%$CL, $M_{t'} < 311$ GeV

2.8 fb$^{-1}$

$0.76$ fb$^{-1}$ Reference: CDF PRL 100 161803 (2008)
Summary

- $M_t = 173.1 \pm 0.6 \pm 1.1$ GeV/c$^2$ (TeV comb.)
- Top charge: not $4/3$ @ 87% CL
- Top width < 13.1 GeV @ 95% CL
- $\sigma = 6.9 \pm 0.4$ (stat) $\pm 0.4$ (syst) $\pm 0.1$ (th) pb
- Afb = 19.3 $\pm 6.5$ (stat) $\pm 2.4$ (syst) %
- No evidence for $ttH$ production
- No evidence for $t^+\rightarrow H+q$
- Top width < 13.1 GeV @ 95% CL
- $f_+ = 0.110 \pm 0.059$ (stat) $\pm 0.052$ (syst)
- No evidence for $t^+\rightarrow H+q$
- No evidence for $ttH$ production
- $B(t^\rightarrow Wb)/B(t^\rightarrow Wq)=0.97 \pm 0.09$
- $\sigma/dM_{tt}$ no discrepancy with SM
- Fraction via gg fusion: $0.07^{+0.15}_{-0.07}$

For details and more on single top, refer to Single Top Observation!!!
• Mini-symposium in Single Top:
  ➡ May 3 2009 10:45AM, Governor's Square 11

• Parallel talks:
  ➡ Top Mass, May 3 2009 1:30PM, Governor's Square 11
  ➡ Top and Higgs Physics, May 5 2009 10:45AM, Governor's Square 11
  ➡ QCD Physics, May 4 2009 1:30 pm, Plaza Court 4

• Experiment’s web pages:
  ❖ http://www-d0.fnal.gov/Run2Physics/top/top_public_web_pages/top_public.html
  ❖ http://www-cdf.fnal.gov/physics/new/top/top.html
Top Physics has entered the realm of precision physics at the Tevatron.

We are studying top from many angles,

- so far experimental measurements agree with SM predictions.

More data is being analyzed,

- more than 5fb\(^{-1}\) on tape (expected >8fb\(^{-1}\) by 2010).

Stay tuned!!
Summary

- $M_t = 173.1 \pm 0.6 \pm 1.1$ GeV/$c^2$ (TeV comb.)
- Top charge: not 4/3 @ 87% CL
- Top width < 13.1 GeV @ 95% CL
- $\sigma = 6.9 \pm 0.4$ (stat) $\pm 0.4$ (syst) $\pm 0.1$ (th) pb
- $A_{FB} = 19.3 \pm 6.5$ (stat) $\pm 2.4$ (syst) %
- Excl. $M_Z' < 820$ GeV at 95% CL
- $d\sigma/dM_{tt}$ no discrepancy with SM
- Fraction via gg fusion: $0.07^{+0.15}_{-0.07}$
- Anom. coupl: no evidence found
- $f_+ = 0.110 \pm 0.059$ (stat) $\pm 0.052$ (syst)
- $B(t \to Wb)/B(t \to Wq) = 0.97 \pm 0.09$
- No evidence for $t \to H^+ b$
- No evidence for $ttH$ production
- Excl. $M_c < 311$ GeV at 95% CL
- No evidence stop pair production

Single Top Observation !!!