Top Pair Production at DØ
electron+jets final state, kinematics method

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Outline

• Fermilab and The Tevatron
• The DØ detector
  – Calorimeter details
• The Top quark
  – Production and decay
  – Cross section measurement
• Summary
DØ at Fermilab

- The Tevatron
- Luminosity
- The DØ Detector
Top Pair Production at DØ

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The Tevatron

- **Cesium gun**
  - Source of H\(^+\) ions
- **Cockcroft Walton**
  - Continuous stream
  - 750 KeV
- **Linac**
  - 100 Mhz, 6.3E\(^{12}\) ions bunches
  - 400 MeV
- **Carbon foil**: H\(^+\) to proton
- **Booster**
  - 12 bunches
  - 8 GeV
- **Main injector**
  - 150 Gev
  - Nickel target: anti-proton source
- **Tevatron**
  - 3 x 12 bunches
  - 980 GeV, \(\sqrt{s}=1.96\) TeV
  - Bunch crossing 396 ns
The Tevatron

Peak luminosity record
\[ \sim 1.6 \times 10^{32} \text{ cm}^{-2} \text{s}^{-1} = 160 \times b^{-1} \text{s}^{-1} \]

Delivered luminosity \( \sim 1.5 \text{ fb}^{-1} \)
\( \sim 5 \text{ fb}^{-1} \) by 2009

Top Pair Production at DØ
The DØ Run II detector

The DØ Run II detector consists of various components including:

- **Liquid argon sampling Calorimeter**
- **End cap calorimeter**
- **Central calorimeter**
- **Coarse hadronic**
- **Fine hadronic**
- **Electromagnetic**

The detector is equipped with the following systems:

- **Muon system**
  - Solenoid B-Field 2 Tesla
  - Toroidal B-Field 1.8 Tesla

- **3 level trigger system**
  - Collision rate 2.5 MHz
  - L1. Calo., track and muon 2 kHz
  - L2. Calo., track, muon and vertex 800 Hz
  - L3. online reconstruction 50 Hz

Additionally, the detector includes:

- **Microstrip tracker and Fiber tracker**
- **Solenoid B-Field 2 Tesla**
- **Liquid argon sampling Calorimeter**

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The DØ detector

~88% data taking efficiency

~1 fb\(^{-1}\) recorded
~480 pb\(^{-1}\) current analysis
The Tevatron and DØ Calorimeter contribution

- Readout chain details
- Readout gain correction
- Zero suppression
- Gain/Linearity calibration
The DØ calorimeter

Readout electronics
- Preamplification
- Shaping
- Level 1 trigger signal
- Gain selection
- Analog memory (SCA L1)
- Baseline subtraction (BLS)
- Analog memory (SCA L2)
- Digitisation (ADC)
- Online reconstruction
- Tape recording

3 sections
Electromagnetic (Ur/Ar)
Fine hadronic (Cu-No/Ar)
Coarse hadronic (Fe/Ar)

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Readout corrections

• Slight problem in synchronisation between BLS and ADC boards
• Selected gain information was sometimes lost (hardware fixed)
• Factor 8,1/8 in cell energy
• Bad estimation of object energy
Readout corrections

- Algorithm for correction uses the L1 trigger information that is redundant.
- Modify (*8, *1/8) cells energy when large L3-L1 transverse energy.
- Test the algorithm on Z→ee⁻ data. It recovers correct electron energy.

Before After

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<tr>
<td>Sigma</td>
<td>2.286 ± 0.2896</td>
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</table>
Noise suppression

- Online suppression at 1.5 $\sigma_{\text{ped}}$
  - Limits data files size
- Offline suppression at 2.5 $\sigma_{\text{ped}}$
  - Decreases the level of noise

Gaussian electronics noise with width $\sigma_{\text{ped}}$
- Elec. $\sim$50 MeV
- Fine Had. $\sim$90 MeV
- Coarse Had. $\sim$300 MeV

- Implementation of the T42 algorithm
  - Keep cells with signal greater than 4 $\sigma_{\text{ped}}$
    and neighboring cells with signal greater than 2.5 $\sigma_{\text{ped}}$
  - Dynamic noise suppression
  - Enhance cluster like energy deposition
  - Reject isolated energy deposition
Noise suppression

Remove noisy jets

Remove uniform energy density

(P_T wo. T42 - P_T w. T42) (GeV)

P_T without T42 (GeV)

no JES corrections
p13 qual cuts

Missing transverse energy decreases

METx (GeV)

METx (GeV)

METx - all layers, no T42 jets

METx - all layers, no T42 jets

Mean 1.038
RMS 7.699

Mean 0.1559
RMS 6.907

mean 1.20
sigma 5.50
X2/N 1.46

mean 0.37
sigma 4.75
X2/N 3.38

-14%

-7%

Significance improves
Electronics calibration

Calorimeter pulser system:
- Artificial signal injected before preamps.
- Digital response as a function of pulse strength.
- Calorimeter readout calibration
  → NLC corrections, ...

SCA ship (analogical memory) have non-linear functioning regions

- Artifical signal injected before preamps.
- Digital response as a function of pulse strength.
- Calorimeter readout calibration
  → NLC corrections, ...

Effect on electron energy resolution:
- 28% on $J/\psi$ mass
- 6% on $Z$ mass

NOT IN CURRENT ANALYSIS

Entries: 207
- Mass: 3.16 (0.04)
- Width: 0.00 (fixed)
- Res.: 0.32 (0.03)
- $122 Z$-Back
- $90 Z$ (0.49)
- S/root(B) 15.9
- chi2/NDF: 13/12

Entries: 183
- Mass: 3.09 (0.04)
- Width: 0.00 (fixed)
- Res.: 0.23 (0.04)
- $80 Z$-Back
- $55 Z$ (7.42)
- S/root(B) 11.0
- chi2/NDF: 6/11

Top Pair Production at DØ
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The Tevatron and DØ Calorimeter contribution
Top Quark Pair Production
→ Production
→ Decay channels
The Top quark

- Discovered in 1995 at Fermilab
  - Electroweck partner of the B quark (1977 Fermilab)
- Large mass 174 GeV
  - Yukawa coupling ~1
  - EW constraint on the Higgs mass
  - Constraint on physics beyond the Standard Model
- Short lifetime $E^{-25}$ s (hadronisation $E^{-23}$ s)
  - Decay as a « free » quark
  - Helicity, spin, mass propagated to decay products

Motivations for top pair production
- Top quark is « new »
- Sensible to new physics
- Large contribution to other analysis background
Top quark production

Strong force vertex: pair production
Cacciari et al., JHEP, 404, 68 (2004)

\[ \bar{q}^2 \rightarrow t \bar{t} \]
85% 15%

Electroweak vertex: single top production

\[ 0.88 \text{ pb} \pm 8\% \quad 1.98 \text{ pb} \pm 11\% \]
Top quark production

At LHC, gluons fusion will dominate (90%) due to gluon PDF overshoot at $x \sim 0.025$

Cross section $\sim$ nb
Rate $\sim$ 10 evts/s
Top quark decay

Within SM, top quarks EW decays electroweakly before hadronisation
CKM matrix element $V_{tb} \sim 1$ (Unitarity with 3 generations)

Top quark predominantly decays into Wb

- b-jet, may be identified with b-tagging

W decay channels
  - Quark pair (67% incl.) : mostly two jets
  - Lepton/neutrino (11% each flavour) : high $p_T$ lepton and missing transverse energy (MET)

→ Top decay channels classified by W decay channels
→ Exotic decays far below current exp. precision
Top pair decay

Three main channels

→ All jets:
  • Both W into quark pair, BR~46%
  • Dominant QCD background

→ Dilepton:
  • Both W into lepton/neutrino, BR(ll)~1.2, BR(ll')~2.4 %
  • Pure but low statistics

→ Lepton+jets:
  • One W into lepton/neutrino, the other into quark pair, BR~15%
  • Compromise between background and statistics
Top pair decay
Lepton+jets channel

• **1 lepton** from W decay or tau decay from W decay
• At least **1 neutrino** : missing transverse energy
• 4 quarks in the final state: mostly **at least 3 jets** (80%)

Branching ratio
BR(e+jets) = 17.1 ± 0.2%

Main backgrounds
➢ W+jets
➢ Multijets: jet/photon fakes an electron

Methods
➢ Use **event kinematics** discrimination not using **b-jets** tagging method
The Tevatron and DØ Calorimeter contribution
Top Quark Pair Production
Cross Section Measurement

- Triggering
- Preselection
- QCD background expectation
- Kinematic discriminant
- Result
- Improvements
Signal triggering

Jets production: $\sim 3 \, \mu b$

W+jets production: $\sim 40 \, pb$

Signal: $6.7 \, pb$

Triggering strategy:
- An electron: reduce the QCD background
- High $p_T$ jets: reduce QCD and W+jets

Trigger filter:
- EM object $p_T > 15 \, GeV$
- 2 JETS $p_T > 15 \, GeV$

Trigger efficiency measured in data
Applied to signal Monte Carlo $\epsilon_{\text{décl.}} = 93\%$
W+jets preselection

Cut:

- At least four good jets \( (p_T \geq 20 \text{ GeV}) \) (fourth inclusive jet multiplicity)
- One electron (loose/tight) with large transverse energy \( (p_T \geq 20 \text{ GeV}) \)
- Some missing tranverse energy \( (\text{MET} \geq 20 \text{ GeV}) \)
- Triangular cut \( (\Delta \phi, \text{MET}) \): remove QCD background
- A good primary vertex
- No isolated muon

Signal preselection efficiency \( \epsilon_{\text{présél.}} = 11\% \)
from signal Monte Carlo, corrected for DATA/MC scale factors
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QCD background expectation

\[ N_L = N_{QCD} + N_{W, \bar{t}t} \]
\[ N_T = \varepsilon_{QCD} N_{QCD} + \varepsilon_{\text{sig}} N_{W, \bar{t}t} \]

\[ \frac{N_{W, \bar{t}t} - \varepsilon_{QCD} \cdot N_L}{\varepsilon_{\text{sig}} - \varepsilon_{QCD}} \]
\[ \frac{\varepsilon_{\text{sig}} \cdot N_L}{\varepsilon_{\text{sig}} - \varepsilon_{QCD}} \]

\[ \varepsilon_{QCD} = 16\% \]
\[ \varepsilon_{\text{signal}} = 81.2\% \]

\[ \text{QCD test sample} \quad \text{« loose » but not « tight »} \]

\[ \text{L sample} \quad \text{« loose »} \]

\[ \text{T sample} \quad \text{« tight »} \]

\[ \text{not hached} \]

\[ \varepsilon_{QCD} : \text{efficiency for a fake « loose » electron to be identified as a « tight » electron} \]

\[ \varepsilon_{\text{signal}} : \text{efficiency for a true « loose » electron to be identified as a « tight » electron} \]
QCD background expectation

Hadron jet fakes an electron ($\pi^0 \to 2\gamma$, $\eta \to 2\gamma$ ...) or radiated photon is reconstructed as an electron

- Rare decay, MC not feasible: estimate the effect from data.

$\epsilon_{\text{QCD}}$: efficiency for a fake "loose" electron to be identified as a "tight" electron

$\epsilon_{\text{QCD}}$ measurement

Full preselected events except for the MET cut.

- QCD events dominate at MET $\leq 10$ GeV

$\epsilon_{\text{QCD}}$ value used (~15%)

QCD fraction in data sample ~16%

stable in all jet multiplicities

QCD cross check

Use the $e\nu$ transverse mass distribution in the Loose and in the Tight samples (template fit method)

Measurements in agreement
Event kinematics

- W boson from top quark are more transverse than in the W+jets background
- Jets are harder in signal events
- QCD and W+jets topology are very similar

→ Build a likelihood function out of six variables that optimize the expected stat+syst error

Variable $x_i \rightarrow \ln \frac{S_i}{(B_i+S_i)} \rightarrow f_i(x)$

→ likelihood probability

$$D = D(x_1, \ldots, x_6) = \frac{\exp\left(\sum_{i=1}^{6} f_i(x_i)\right)}{\exp\left(\sum_{i=1}^{6} f_i(x_i)\right) + 1}$$
Event kinematics discriminant

- Signal peaks at 1
- W+jets peaks at 0

QCD and Z+jets backgrounds have same shape as W+jets: two-class likelihood is enough

Top pair to dilepton contribution shares the event topology
Analysis in e+jets channel

Triggering and preselection

- Fourth inclusive jet multiplicity
- Estimation of QCD background purely from data
- Dilepton channel contamination relative to signal estimated

Likelihood optimisation

- Kinematics discriminant distribution
discriminate signal from background

- QCD background estimation
discriminate QCD from W+jets

230 pb\(^{-1}\), Published result

\[
\sigma_{t\bar{t}}^{\text{Kine. electron+jets}} = 8.2^{+2.1}_{-1.9}\text{(stat)}^{+1.9}_{-1.3}\text{(syst)} \pm 0.5\text{(lumi)}\text{pb}
\]

Top Pair Production at DØ

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Analysis in lepton+jets channels

Triggering and preselection
- Fourth inclusive jet multiplicity
- Estimation of QCD background purely from data
- Dilepton channel contamination relative to signal estimated

Likelihood optimisation
- Kinematics discriminant distribution
discriminate signal from background
- QCD background estimation
discriminate QCD from W+jets

Top Pair Production at DØ
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Top Pair Production at DØ

Dr. Jean-Roch Vlimant, 14 Dec 2005

230 pb⁻¹, Published result

$$\sigma_{\text{Kine.lepton+jets}}^{\text{t\bar{t}}} = 6.7^{+1.4}_{-1.3}\text{(stat)}^{+1.6}_{-1.1}\text{(syst)} \pm 0.4\text{(lumi)} \text{ pb}$$
Analysis improvements

Improvements forseen
• Using event with at least 3 jets to double the signal statistics
  ➔ Better expected statistical error (26% → 19%)
    even though S/B decreases
  ➔ Less jet systematics (22% → 15%)
• Improved systematics treatment
  ➔ More accurate estimation
  ➔ Recent development in jet related systematics calculation
• Improved fitting method, QCD background expectation
  ➔ Use W transverse mass distribution to discriminate QCD
  ➔ No triangular cut ($\Delta \varphi, \text{MET}$) (19% → 17%)

• ~4 times luminosity data sample to come
  ➔ Stat. Uncertainty decrease by factor 2
Summary

- DØ has precise measurements of Top pair production cross section
- Results are in agreement with SM expectation
- Best single Top production cross section limit
- Controled samples for Top properties measurements
- Even more precise measurement foreseen with 1fb⁻¹ recorded
  - Half stat error
  - Work on the main sources of systematic uncertainty
  - Improved method
- Single top observation by 2006
Summary

● The Tevatron is the only running collider for Top quark physics
  – Production and properties
  – *Electroweak production observation soon*
● DØ data quality has been significantly improved over last years.
  – Improved systematics and energy resolution
● More than 1fb⁻¹ recorded for analysis in the pipeline
● Analysis are constantly improving
● Far into precision era at the Tevatron: CDF and DØ.
Backup Slides

➔ b-Tagging
➔ Cross Section
  • All jets channel
  • Dilepton channel
  • Lepton+jets b-tagging
➔ Top quark properties
  • Mass
  • Helicity
  • Branching ratio
➔ lepton+jets b-tag
B-tagging

- B-hadrons (lifetime ~1.5 ps) don't decay at PV
- SV significantly displaced (500µm to few mm) from PV
- B decay tracks with large PV impact parameter (d0)

b-jet identification

SVT (secondary vertex tagger)
- 1+ jets signal b-tag. eff.
  - 45% with 1 tag
  - 15% with 2 tags

Jet $p_T$ (GeV)

Efficiency

- b-jet efficiency
- c-jet efficiency
- mis-tagging rate ($\times 10$)
Single Top production

SM cross section of the order 3 pb (~half of pair production)
But overwhelming background from any lepton+2 jets+MET events
  ➢ Top pair production
  ➢ W+jets, di-bosons production

Top Pair Production at DØ

DØ preliminary result with 370 pb$^{-1}$
~370 1-btag lepton+jets events
(370±27 back. 19±2 exp. signal)
Signal expectation is consistent with background uncertainty
No observation yet
Limits on cross section are set
  ➢ s-channel < 6.4 pb (95% C.L.)
  ➢ t-channel < 5.0 pb (95% C.L.)

➢ Need 1.5 fb$^{-1}$ for observation (by 2006)
➢ Need 4.5 fb$^{-1}$ for discovery (by 2009)
Top pair production
Alljet channel

• At least 6 jets
  - 0.5 cone jets
  - $p_T > 15$ GeV, $|\eta| < 2.8$

• At least one b-tagged jet

• Neural Net. on 6 Kinematics variables
  - NN>0.9

• Main systematics
  - Jet Energy calibration
  - Jet reconstruction
  - Tagging efficiency

350 pb$^{-1}$, Preliminary result
\[ \sigma_{t\bar{t}}^{\text{alljets}} = 5.2^{+2.6}_{-2.5} \text{(stat)} + 1.5_{-1.0} \text{(syst)} \pm 0.3 \text{(lumi)} \text{ pb} \]
Top pair production
Dilepton channel

- At least **2 jets**
  - 0.5 cone jets
  - $p_T > 35$ GeV, $|\eta| < 2.5$
- **2 leptons** (ee, e$\nu$, $\nu\nu$)
  - $p_T > 15$ GeV
  - Electron $|\eta| < 1.1$ or $1.5 < |\eta| < 2.5$
  - Muon $|\eta| < 2.0$
- At least **2 neutrinos**
  - $E_T^{miss} > 25$ GeV

Event counting analysis

Backgrounds
- QCD (fake leptons)
- Dibosons production
- $Z/\gamma \rightarrow$ dilepton

Main systematics
- Jet Energy calibration
- Jet reconstruction
- Lepton identification

370 pb$^{-1}$, Preliminary result

$$\sigma_{t\bar{t}}^{dilepton} = 8.6^{+2.2}_{-2.0}^{(stat)} 1.2^{(syst)} \pm 0.6^{(lumi)} \text{pb}$$

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Analysis using b-tagging

Lepton+jet trigger, 
$W(\rightarrow \ell \nu)+\text{jets (p}_{T}>15\text{ GeV})$ selection

- Third and fourth inclusive jet multiplicity
- Estimation of QCD background purely from data
- W+jets normalisation from data
  - $W+$jets Flavor composition from MC simulation
- Other backgrounds from NLO cross sections
  - single top, diboson

Likelihood optimisation

- Estimation of number of events with 1 and 2 jets tagged
  - Determine the signal content in 8 independent channels
- Nuisance of systematic sources
  - Allow for shift of Xsec

Top Pair Production at DØ

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Analysis using b-tagging

Top enriched sample

Presence of W boson

Large transverse energy

Systematics:
- W+jets flavor: 11%
- btag efficiency: 5%

370 pb⁻¹, Preliminary result

σ_{btag, lepton+jets}^{ttj} = 8.1^{+1.3}_{-1.2} (stat + syst) ± 0.5 (lumi) pb
Top Quark Properties
Top quark properties

From top enriched sample with little, controlled background, Top quark properties can be study

- Top quark mass
  
  Yukawa couling $\sim 1$

- Top quark and W helicity
  
  test V-A theory, find exotic Top decay

- $t \rightarrow Wb$ branching ratio
  
  test of SM, $V_{tb}$ measurement
Top quark mass

• Top quark mass enters the EW constraint on the Higgs mass. Even constraint of physics beyond SM
• Need a sample as pure as possible in top quark pairs
  ➔ Lepton+jets: have to control the backgrounds
  ➔ Dilepton: pure, but very few events
• Need to reconstruct the decay kinematics
  ➔ Constraint fit with W boson mass and 2 equal Wb masses: low bias template method
  ➔ Use kinematics directly from matrix elements: matrix elements method
Top quark mass
Lepton+jets channel
low bias template method

- Increase purity
  - Use kinematics discriminant
  - b-tagging (shown below)
- Reconstruct event kinematics with constraint fit
- Fit top mass distribution to MC with different assumption of Top mass

![Graphs showing top quark mass distribution and fit mass vs. events]
Top quark mass
Matrix element method

- Calculate probability to have the observed final state from matrix element and PDFs.
  - Peak mass in dilepton channel. Fit peak mass distribution with MC
  - Top mass in lepton+jet channel. Most probable value.

Dilepton channel

Lepton+jets channel

- \(-\ln L(JES, m_{\text{top}})\)
- 320 pb\(^{-1}\)
- Most probable Top mass
- Most probable JES

Top Pair Production at DØ

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Top quark mass

- DØ contributes to Top quark mass world average
- Same order of precision than RunI results
  - Different detector (B field, calorimeter elec.)
  - Still working on main systematics (JES)

Mass of the Top Quark (*Preliminary*)

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<th>Measurement</th>
<th>$M_{top}$ [GeV/c$^2$]</th>
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<tbody>
<tr>
<td>CDF-I di-$l$</td>
<td>167.4 ± 11.4</td>
</tr>
<tr>
<td>DØ-I di-$l$</td>
<td>168.4 ± 12.8</td>
</tr>
<tr>
<td>CDF-II di-$l^*$</td>
<td>165.3 ± 7.3</td>
</tr>
<tr>
<td>CDF-I $l$+$j$</td>
<td>176.1 ± 7.3</td>
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<tr>
<td>DØ-I $l$+$j$</td>
<td>180.1 ± 5.3</td>
</tr>
<tr>
<td>CDF-II $l$+$j^*$</td>
<td>173.5 ± 4.1</td>
</tr>
<tr>
<td>DØ-II $l$+$j^*$</td>
<td>169.5 ± 4.7</td>
</tr>
<tr>
<td>CDF-I all-$j$</td>
<td>186.0 ± 11.5</td>
</tr>
<tr>
<td>Tevatron Run-I/II$^*$</td>
<td>172.7 ± 2.9</td>
</tr>
</tbody>
</table>

$\chi^2$/dof = 6.5/7
Top quark and W helicity

Top quark decays before hadronization
Massless b-quark has negative helicity
Right handed W boson is rare

Longitudinally polarized fraction

\[
f_0 = \frac{m_t^2}{2M_W^2 + m_t^2 + m_b^2} = (70.1 \pm 1.6)\%
\]

Left handed fraction

\[
f_- \approx 30\%
\]

Right handed fraction

\[
f_+ \approx 0\%
\]

(Forbidden if \(m_b = 0\))
Top quark and W helicity

- Study lepton angular distribution in $W(\rightarrow l\nu)$ rest frame with respect to Top quark momentum
- Consistent with no right handed W boson

**Theory**

**Experiment**

230 pb$^{-1}$, Published result

$$f_+ = 0.00 \pm 0.13{\text{(stat)}} \pm 0.07{\text{(syst)}}, \quad f_+ < 0.25 @ 95\% \text{ C.L.}$$
Top → Wb branching ratio

- Lepton+jets final state
- Events with 3 or more than 4 jets
- Breakdown into 0-tag, 1-tag, 2-tag

\[ P_{n\text{-tag}} = R^2 P_{n\text{-tag}}(bb) + 2R(1-R)P_{n\text{-tag}}(bq) + (1-R)^2 P_{n\text{-tag}}(qq) \]

230 pb\(^{-1}\), preliminary result

\[ R = 1.03^{+0.19}_{-0.17}(\text{stat+syst}), \quad (R > 0.64, \quad |V_{tb}| > 0.80) @ 95\% \ C.L. \]