Top Quark Physics
At Hadron Colliders

Frédéric Déliot
CEA-Saclay

Results from the Atlas, CDF, CMS and D0 collaborations


EPS-HEP Conference, Grenoble, 25-July-2011
Hadron Colliders

**Tevatron, Fermilab**

- *pp* collider, $\sqrt{s} = 1.96$ TeV

Run II started in 2002, will end Sep. 30th 2011, expected to deliver $\sim 12$ fb$^{-1}$

- Results presented here up to $\sim 5.8$ fb$^{-1}$

**LHC, CERN**

- *pp* collider, $\sqrt{s} = 7$ TeV

started in 2009, 1st phase until end of 2012, expected to deliver 2-5 fb$^{-1}$ at the end of 2011

- Results presented here up to $\sim 1.1$ fb$^{-1}$
Why Do We Study the Top Quark?

- It is the heaviest elementary particle

\[ \mathcal{L}_{\text{Yukawa}} = -\lambda_t \bar{\psi}_L \Phi \psi_R \]

\[ \lambda_t \approx 1 \]

\[ m_t \gg m_b \]

\[ \tau \approx 5 \times 10^{-25} \text{s} \ll \Lambda_{\text{QCD}}^{-1} \]

- coupling to the Higgs boson close to 1: special role in the electroweak symmetry breaking?

- decay before hadronizing: unique way to observe a bare quark

The top quark is a special quark!
Special sector to search for new physics
Direct Search For New Physics in the Top Sector

- look for specific new models that involve top signatures or for new particles that decay like tops

new particle ?

new couplings (FCNC) ?

search for $t\bar{t}$ resonance

l+jets

all-jets

see talks by A. Duperrin (Tevatron), D. Charlton (Atlas), G. Tonelli (CMS) and the parallel session talks
Model Independent Search for New Physics with Tops

- look for deviations from the Standard Model expectation:
  - precisely measure the top properties
  - new physics effects could be seen as new or anomalous couplings

for example:

Different top observables can constrain different new physics effects
Top Quark Pair Production at Hadron Colliders

- main production: $t\bar{t}$ pairs via strong interaction

The Tevatron is a quark-antiquark annihilation machine
The LHC is a gluon fusion machine

for $m_t = 172.5$ GeV:

- $\sigma(p\bar{p} \to t\bar{t})_{\text{NNLOapprox}} = 7.46^{+0.48}_{-0.67}$ pb
- $\sigma(pp \to t\bar{t})_{\text{NNLOapprox}} = 164.6^{+11.4}_{-15.7}$ pb

* Langenfeld et al. PRD 80, 054009 (2009)
* Ahrens et al., JHEP 1009, 097 (2010), arXiv:1105.5824

with 1 fb$^{-1}$ at LHC, ~ 4 times more $t\bar{t}$ than at Tevatron with 5 fb$^{-1}$
Electroweak Top Production At Hadron Colliders

- discovered in 2009 at the Tevatron
  PRL 103, 092001 (2009), PRL 103, 092002 (2009)
- allows to directly measure $V_{tb}$
- challenging to measure
  - small cross section and background similar signature than signal

Interesting to measure the 3 processes separately
  tW not possible at Tevatron, s-channel very challenging at LHC
Top Quark Pair Signatures

- within the Standard Model: $B(t \rightarrow Wb) \approx 1$
  - could be modified by new physics
- top pair signatures classified according to the $W$ decays

### dilepton: small rate, small background
main background: Drell-Yan: fake missing $E_T$ (estimated from data)

### alljets: large rate, large background
main background: multijet (estimated from data)

### l+jets: good rate, reasonable background
main backgrounds:
  - $W$+jets (shape: MC, normalization: data)
  - multijet: fake lepton (estimated from data)

### b-quark jet identification
often used to enhance S/B
Top Quark Production
Lepton + Jets Top Pair Cross Section

- **most precise channel**
  - measurements with or without b-tagging
  - usually fit the number of $W$+jets together with the number of $t\bar{t}$
  - can also fit the systematic uncertainties to reduce them

**discriminating variables:**
- $N_{jets}=3$: MET
- $N_{jets} \geq 4$: $M_3 = M_{jjj}$

**likelihood including**
- kinematic observables and b-tagging information

**dominant systematics:**
- Jet Energy Scale (JES), Jet ID, b-tagging, $W$+HF fraction

---

Frédéric Déliot, EPS 2011, Grenoble, 25-JULY-2011
Top Pair Cross Sections In the Other Channels

- interest:
  - measurements in different signal/background environment
  - see if all decay channels give the same cross section

CMS:
- alljets
- CMS: $\mu\tau$

Atlas: dilepton

Agreements between the different decay channels

- in addition to the cross section
  - fit together cross section and $R$:

$$ R = \frac{B(t \to Wb)}{B(t \to Wq)} = \frac{|V_{tb}|^2}{|V_{tb}|^2 + |V_{ts}|^2 + |V_{td}|^2} $$

SM predicts $R = 1$

ljets+dilepton: $|V_{tb}| = 0.95 \pm 0.02$ assuming CKM unitarity

(agreeement with the SM: 1.6 %)

Frédéric Déliot, EPS 2011, Grenoble, 25-JULY-2011
Measurements agree with the QCD predictions

Future measurements will focus on differential cross sections
**t-Channel Single Top Cross Section**

- **analysis strategy**
  - discriminate signal (t-channel) from background (other single top, W+jets, t̅t̅):
    * Tevatron: multivariate (Neural Networks, Boosted Decision Trees, ...)
    * LHC: cut-based or multivariate

- **observation:** 5.5σ
  - **ATLAS:** 0.7 fb⁻¹
  - **CMS:** 36 pb⁻¹, √s = 7 TeV

- **σ_{tq̅b} (pb) for m_t = 172.5 GeV:**
  - CDF (3.2 fb⁻¹): 0.8 ± 0.4
  - D0 (5.4 fb⁻¹, arXiv:1105.2788): 2.90 ± 0.59  **5.5σ**
  - CMS (36 pb⁻¹, arXiv:1106.3052): 83.6 ± 29.8 (stat + syst) ± 3.3 (lumi)  **3.7σ**
  - Atlas (0.7 fb⁻¹): 90^{+32}_{−22}  **7.6σ**

- **New:**
  - **2D fit:** \( \cos(l, \text{light } j) \)
  - **boosted decision tree (BDT)**

- **combination of 3 multivariate discriminants**

---

Frédéric Déliot, EPS 2011, Grenoble, 25-JULY-2011
Other Single Top Cross Sections

- inclusive cross section at the Tevatron
  - signal: both $t$ and $s$-channel

- search for $Wt$ channel in the dilepton channel
  - cut based
  - main background: $t\bar{t}$

\[ \sigma(pp \rightarrow Wt + X) < 39.1 \text{ pb} \]

\[ D0 \ (5.4 \text{ fb}^{-1}) \text{ for } m_t = 172.5 \text{ GeV}: \]
\[ \begin{align*}
\sigma_{tb} & : 0.68_{-0.35}^{+0.38} \text{ pb} \\
\sigma_{tb/tqb} & : 3.43_{-0.74}^{+0.73} \text{ pb}
\end{align*} \]

need more statistics for $s$-channel sensitivity

\[ |V_{tb}| > 0.79 \text{ at 95\% CL for } 0 \leq V_{tb} \leq 1 \]
Top Quark Properties
Top Quark Mass

- why measuring the top mass precisely?
  - free parameter of the SM
  - predict the Higgs boson mass together with the W boson mass
  - consistency of the SM and possibly with the direct Higgs measurements

- how to measure the top mass?
  - template method:
    * compare an observable in data with MC generated with different masses
  - matrix element method:
    * build an event probability based on the LO $t\bar{t}$ matrix element
    * using the full kinematics of the event
  - ideogram method:
    * event likelihood computed as a convolution of a Gaussian resolution function with a Breit-Wigner (signal)

- for channel with at least one W decaying hadronically, can calibrate the jet energy scale (JES) constraining $M_{jj}$ to $M_W$
- need to calibrate the method to correct for any potential biases
Top Quark Mass Measurements

- **CDF template result using MET+jets events**
  - NN selection to extract the signal
  - observables: \( M_t: M_3 = M_{jjj}, M_3' = M_{jjj}' \), JES: \( M_2 = M_{jj} \)

  \[
  M_{\text{top}} = 172.3 \pm 2.4 \text{ (stat. + JES)} \pm 1.0 \text{ (syst.) GeV/c}^2
  \]

- **D0 ME result using lepton+jets events**
  - new flavor-dependent jet response correction
  - combine with the previous 1 fb\(^{-1}\) measurement

  \[
  m_t = 174.94 \pm 0.83\text{(stat)} \pm 0.78\text{(JES)} \pm 0.96\text{(syst)} \text{ GeV}
  \]

- **CMS ideogram result using lepton+jets events**
  - systematically limited: signal modeling, residual JES
  - dominant systematics: JES, factorization scale
Top Quark Mass Summary

- new Tevatron combination
  - uncertainty below 1 GeV for the first time
  - all channels give consistent results
  - still working on decreasing the systematic uncertainties

- new electroweak fit, constraints on the Higgs boson mass:
  - $m_H < 161$ GeV at 95% CL ($m_H < 185$ with LEP limit)
  - $m_H = 92^{+34}_{-26}$ GeV

Frédéric Déliot, EPS 2011, Grenoble, 25-JULY-2011
**W Boson Helicity In Top Decays**

**Motivation:**
- Test the SM at the electroweak scale
- New physics could affect the helicity, no right-handed W in the SM

**Measurement Methods:**
- Template fit of the $\cos \theta^* \text{ distribution}$
  (angle between the lepton from the W boson and the top direction in W boson rest frame)
- Matrix element (ME)

**Combination of the latest Tevatron results:**
- Taken correlation into account both when $f_0$ and $f_+$ are floating or only one of them

$$f_0 = 0.732 \pm 0.063(\text{stat}) \pm 0.052(\text{syst})$$
$$f_+ = -0.039 \pm 0.034(\text{stat}) \pm 0.030(\text{syst})$$

(2D)

**Atlas Result:**
- Lepton+jets template (35 pb$^{-1}$)

$$f_0 = 0.59 \pm 0.10(\text{stat}) \pm 0.07(\text{syst})$$
$$f_- = 0.41 \pm 0.10(\text{stat}) \pm 0.07(\text{syst})$$

(1D)
Top Pair Spin Correlations

- **in the SM**, the spin of the top and of the antitop are produced correlated
  - correlation preserved in the decay products
  - can be affected by new physics

- **measurement methods:**
  - template fit of the $\cos \theta_1 \cos \theta_2$ distribution
  ($\theta$ : angle from the down-type fermion wrt spin basis in the top/antitop rest frame)

\[ \frac{1}{\sigma} \frac{d^2 \sigma}{d \cos \theta_1 d \cos \theta_2} = \frac{1}{4} \left( 1 - C \cos \theta_1 \cos \theta_2 \right) \]

- helicity basis, $C_{SM}$: 0.40

[Graph showing experimental data and results]

- **PRD83, 031104, (2011)**

- **ljets**

- **dilepton**

Still statistically limited, close to 3 $\sigma$ sensitivity

- matrix element: measure $f$: fraction of events with spin correlation using a template fit of $R$

\[ R = \frac{P_{sgn}(H = c)}{P_{sgn}(H = u) + P_{sgn}(H = c)} \]

- using ME without spin corr.
- using ME with spin corr.

- **Frédéric Déliot, EPS 2011, Grenoble, 25-JULY-2011**

- **arXiv:1104.5194**

- **DØ, L=5.4 fb^{-1}**

- **N_{events}**

- **$\kappa=0.60\pm0.50\pm0.16$**
Top-Antitop Charge Asymmetry

- At NLO, QCD predicts an asymmetry for $t\bar{t}$ produced via $q\bar{q}$ initial state
  - the top quark is predicted to be emitted preferably in the direction of the incoming quark
  - the exchange of new particles like Z' or axigluon could modify it

\[
\Delta y = y_t - y_{\bar{t}}
\]

\[
A_{t\bar{t}} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}
\]

\[
A_C = \frac{N(\Delta |Y| > 0) - N(\Delta |Y| < 0)}{N(\Delta |Y| > 0) + N(\Delta |Y| < 0)}
\]

\[
\Delta |Y| = |Y_t| - |Y_{\bar{t}}|
\]

forward-backward asymmetry

central-forward asymmetry

smaller at LHC since low $q\bar{q}$ fraction
Tevatron Top Charge Asymmetry Results

- **CDF measurements**
  - CDF measurements
  - D0 ljets measurement
    - unfold the reconstructed distribution to correct for acceptance and detector effects

\[
A_{FB} = \frac{N(q_{ly} > 0) - N(q_{ly} < 0)}{N(q_{ly} > 0) + N(q_{ly} < 0)}
\]

- CDF measurements
  -unfolded data: 0.158 ± 0.074
  - SM prediction (MCFM): 0.058 ± 0.009
  - 0.475 ± 0.114
  - 0.088 ± 0.013
  - 0.42 ± 0.16
  - 0.06 ± 0.01
  - 3.4 \sigma difference

- D0 ljets measurement
  - unfold the reconstructed distribution to correct for acceptance and detector effects

\[
\begin{array}{|c|c|c|}
\hline
 & A_{FB} (%) & \\
\hline
\text{Data} & 9.2 \pm 3.7 & 19.6 \pm 6.5 \\
\text{MC@NLO} & 2.4 \pm 0.7 & 5.0 \pm 0.1 \\
\hline
\end{array}
\]

\[
\begin{array}{|c|c|c|}
\hline
 & A_{FB} (%) & \\
\hline
\text{Data} & 14.2 \pm 3.8 & 15.2 \pm 4.0 \\
\text{MC@NLO} & 0.8 \pm 0.6 & 2.1 \pm 0.1 \\
\hline
\end{array}
\]

- Statistically limited measurements, need better understanding of the predictions

Frédéric Déliot, EPS 2011, Grenoble, 25-JULY-2011
LHC Top Charge Asymmetry Results

- different observables

\[ A_C = \frac{N(\Delta > 0) - N(\Delta < 0)}{N(\Delta > 0) + N(\Delta < 0)} \]

- **Atlas:** \[ \Delta y = |y_t| - |y\bar{t}| \]

- **CMS:** \[ \Delta \eta = |\eta_t| - |\eta\bar{t}| \]

\[ \Delta y^2 = (y_t - y\bar{t})(y_t + y\bar{t}) \]

Currently no deviation from the predictions

Frédéric Déliot, EPS 2011, Grenoble, 25-JULY-2011
**Summary and Conclusion**

We are looking forward for exciting discoveries in the top quark sector.

<table>
<thead>
<tr>
<th>Property</th>
<th>Measurement</th>
<th>SM Prediction</th>
<th>Luminosity (fb⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \sigma_{t\bar{t}} ) (for ( M_t = 172.5 ) GeV)</td>
<td>( pp \rightarrow t\bar{t} )</td>
<td>CDF: ( 7.5 \pm 0.31 ) (stat) ( \pm 0.34 ) (syst) ( \pm 0.15 ) (theory) pb</td>
<td>( 7.46^{+0.48}_{-0.67} ) pb</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Do: ( 7.56^{+0.63}_{-0.56} ) (stat + syst + lumi) pb</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Atlas: ( 180 \pm 9 ) (stat) ( \pm 15 ) (syst) ( \pm 6 ) (lumi) pb</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>CMS: ( 158 \pm 10 ) (uncor.) ( \pm 15 ) (cor.) ( \pm 6 ) (lumi) pb</td>
<td></td>
</tr>
<tr>
<td>( \sigma_{tbq} ) (for ( M_t = 172.5 ) GeV)</td>
<td>( pp \rightarrow t\bar{t} )</td>
<td>CDF: ( 0.8 \pm 0.4 ) pb ( (M_t = 175 ) GeV)</td>
<td>( 2.26 \pm 0.12 ) pb</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Do: ( 2.90 \pm 0.59 ) pb</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Atlas: ( 90^{+32}_{-22} ) pb</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>CMS: ( 93.7 \pm 29.8 ) (stat + syst) ( \pm 3.3 ) (lumi) pb</td>
<td></td>
</tr>
<tr>
<td>( \sigma_{tb} ) (for ( M_t = 172.5 ) GeV)</td>
<td>( pp \rightarrow t\bar{t} )</td>
<td>CDF: ( 1.3^{+0.7}_{-0.5} ) pb ( (M_t = 175 ) GeV)</td>
<td>( 1.04 \pm 0.04 ) pb</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Do: ( 0.68^{+0.38}_{-0.32} ) pb</td>
<td></td>
</tr>
<tr>
<td>( \sigma_{Wt} ) (for ( M_t = 172.5 ) GeV)</td>
<td>( pp \rightarrow t\bar{t} )</td>
<td>Atlas: ( &lt; 39.1 ) pb</td>
<td>( 15.7 \pm 1.4 ) pb</td>
</tr>
<tr>
<td>(</td>
<td>V_{tb}</td>
<td>) ( \geq 0.11 ) (stat + syst) ( \pm 0.07 ) (theory)</td>
<td>CDF: ( 0.91 )</td>
</tr>
<tr>
<td></td>
<td>Do: (</td>
<td>V_{tb}</td>
<td>= 1.02^{+0.10}_{-0.09} )</td>
</tr>
<tr>
<td>( R = B(t \rightarrow Wb)/B(t \rightarrow Wq) )</td>
<td>CDF: ( &gt; 0.61 ) @ 95% CL</td>
<td>1</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td>Do: ( 0.90 \pm 0.04 )</td>
<td>5.4</td>
<td></td>
</tr>
<tr>
<td>( \sigma(gg \rightarrow t\bar{t})/\sigma(pp \rightarrow t\bar{t}) )</td>
<td>( pp \rightarrow t\bar{t} )</td>
<td>CDF: ( 0.07^{+0.15}_{-0.07} )</td>
<td>0.18</td>
</tr>
<tr>
<td>( M_t )</td>
<td>Tev: ( 173.2 \pm 0.9 ) GeV</td>
<td>-</td>
<td>up to 5.8</td>
</tr>
<tr>
<td></td>
<td>Atlas: ( 169.3 \pm 6.3 ) GeV</td>
<td>-</td>
<td>0.035</td>
</tr>
<tr>
<td></td>
<td>CMS: ( 173.4 \pm 3.3 ) GeV</td>
<td>-</td>
<td>0.036</td>
</tr>
<tr>
<td>( M_t - M_Z )</td>
<td>CDF: ( -3.3 \pm 1.4 ) (stat) ( \pm 1.0 ) (syst) GeV</td>
<td>0</td>
<td>5.6</td>
</tr>
<tr>
<td></td>
<td>Do: ( 0.8 \pm 1.8 ) (stat) ( \pm 0.5 ) (syst) GeV</td>
<td>3.6</td>
<td></td>
</tr>
<tr>
<td>( W ) helicity fraction</td>
<td>Tev: ( f_0 = 0.732 \pm 0.063 ) (stat) ( \pm 0.052 ) (syst)</td>
<td>0.7</td>
<td>up to 5.4</td>
</tr>
<tr>
<td></td>
<td>Atlas: ( f_0 = 0.59 \pm 0.10 ) (stat) ( \pm 0.07 ) (syst)</td>
<td>0.7</td>
<td>0.035</td>
</tr>
<tr>
<td>Charge</td>
<td>CDF: ( \leq 4/3 ) excluded @ 95% CL</td>
<td>2/3</td>
<td>5.6</td>
</tr>
<tr>
<td></td>
<td>Do: ( \leq 4/3 ) excluded @ 92% CL</td>
<td>0.37</td>
<td></td>
</tr>
<tr>
<td>( \Gamma_t )</td>
<td>CDF: ( &lt; 7.6 ) GeV @ 95% CL</td>
<td>1.26 GeV</td>
<td>4.3</td>
</tr>
<tr>
<td></td>
<td>Do: ( 1.99^{+0.99}_{-0.55} ) GeV</td>
<td>up to 2.3</td>
<td></td>
</tr>
<tr>
<td>spin correlation</td>
<td>( C_{beam} ) CDF: ( 0.72 \pm 0.64 ) (stat) ( \pm 0.26 ) (syst)</td>
<td>( 0.777^{+0.027}_{-0.042} )</td>
<td>5.3</td>
</tr>
<tr>
<td></td>
<td>Do: ( 0.57 \pm 0.31 ) (stat + syst)</td>
<td>5.4</td>
<td></td>
</tr>
<tr>
<td>Charge asymmetry</td>
<td>( pp \rightarrow t\bar{t} ) CDF: ( 0.158 \pm 0.074 )</td>
<td>0.06</td>
<td>5.3</td>
</tr>
<tr>
<td></td>
<td>Do: ( 0.196 \pm 0.065 )</td>
<td>5.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>( pp \rightarrow t\bar{t} ) Atlas: ( A^C = -0.024 \pm 0.016 ) (stat) ( \pm 0.023 ) (syst)</td>
<td>0.006</td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td>CMS: ( A^C = -0.016 \pm 0.030 ) (stat) ( \pm 0.010 ) (syst)</td>
<td>0.013</td>
<td>1.1</td>
</tr>
</tbody>
</table>

Frédéric Déliot, EPS 2011, Grenoble, 25-JULY-2011
Backup
The Detectors