Expectations for first single top studies in CMS in pp-collisions

Jeannine Wagner-Kuhr
Institut für Experimentelle Kernphysik, KIT
on behalf of the CMS Collaboration

Workshop on Deep Inelastic Scattering and Related Subjects

Florence, 20.4.2010
Overview

- Introduction
- Early single top analysis
  - Event selection
  - QCD estimation
  - Robust sensitive variable
- Prospects

(CMS PAS TOP-09-005)
LHC and CMS

CMS int. luminosity: 2010 (7 TeV)

- Delivered 0.347 nb⁻¹
- Recorded 0.299 nb⁻¹

7 TeV pp-collision event
# Single Top @ LHC

### Diagrams

- **s-channel**
  - Process: $u \rightarrow W^+ V_{tb} \rightarrow t \bar{b}$
  - $d \rightarrow W^- V_{tb} \rightarrow b \bar{b}$

- **t-channel**
  - Process: $u \rightarrow W^+ V_{tb} \rightarrow t \bar{b}$
  - $d \rightarrow W^- V_{tb} \rightarrow b \bar{b}$

- **Associated production**
  - Process: $g \rightarrow W^+ V_{tb} \rightarrow t \bar{b}$

### Cross Sections

<table>
<thead>
<tr>
<th>Source</th>
<th>Tevatron [pb] $\sqrt{s}=1.96$ TeV</th>
<th>LHC [pb] $\sqrt{s}=7$ TeV</th>
<th>LHC [pb] $\sqrt{s}=10$ TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) PRD 74, 114012 (2006)</td>
<td>1.0 1)</td>
<td>3</td>
<td>5 2)</td>
</tr>
<tr>
<td>2) values scaled to 10TeV based on PRD 70, 114012 (2004); Nucl. Phys. B726, 109 (2005)</td>
<td></td>
<td>65</td>
<td>124 3)</td>
</tr>
<tr>
<td>3) JHEP 0910, 042 (2009)</td>
<td>0.26 1)</td>
<td>11</td>
<td>29 2)</td>
</tr>
</tbody>
</table>

---

DIS 2010, Florence, 20.4.2010

Jeannine Wagner-Kuhr

4
Single Top @ LHC

s-channel

\[ u \rightarrow W^+ V_{tb} \]
\[ \bar{d} \rightarrow W^- \]

\[ t \rightarrow b V_{tb} \]
\[ \bar{b} \rightarrow b \]

\[ W^+ \]
\[ V_{tb} \]

\[ t \rightarrow W^+ V_{tb} \]
\[ u \rightarrow t b \]

\[ g \rightarrow t b V_{tb} \]

Associated production

1) PRD 74, 114012 (2006)
2) values scaled to 10 TeV based on PRD 70, 114012 (2004); Nucl. Phys. B726, 109 (2005)
3) JHEP 0910, 042 (2009)

<table>
<thead>
<tr>
<th></th>
<th>Tevatron [pb]</th>
<th>LHC [pb]</th>
<th>LHC [pb]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\sqrt{s}=1.96$ TeV</td>
<td>$\sqrt{s}=7$ TeV</td>
<td>$\sqrt{s}=10$ TeV</td>
</tr>
<tr>
<td>s-channel</td>
<td>1.0 $^1$</td>
<td>3</td>
<td>5 $^2$</td>
</tr>
<tr>
<td>t-channel</td>
<td>2.2 $^1$</td>
<td>65</td>
<td>124 $^3$</td>
</tr>
<tr>
<td>Associated production</td>
<td>0.26 $^1$</td>
<td>11</td>
<td>29 $^2$</td>
</tr>
</tbody>
</table>

Discovered spring 2009

Jeannine Wagner-Kuhr
Single Top @ LHC

---

**Physics motivation:**

- Direct measurement of $|V_{tb}|^2$
- Test of $Wtb$ coupling
- Search for new physics
  
  *(4th gen., $H+$, $W'$ ...)*

---

**Table:**

<table>
<thead>
<tr>
<th></th>
<th>Tevatron [pb]</th>
<th>LHC $\sqrt{s}=7$ TeV</th>
<th>LHC $\sqrt{s}=10$ TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>s-channel</td>
<td>1.0</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>t-channel</td>
<td>2.2</td>
<td>65</td>
<td>124</td>
</tr>
<tr>
<td>Associated production</td>
<td>0.26</td>
<td>11</td>
<td>29</td>
</tr>
</tbody>
</table>

---

1) PRD 74, 114012 (2006)
2) values scaled to 10 TeV based on PRD 70, 114012 (2004); Nucl. Phys. B726, 109 (2005)
3) JHEP 0910, 042 (2009)

---

Discovered spring 2009
Single Top @ LHC

Physics motivation:

- Direct measurement of $|V_{tb}|^2$
- Test of $Wtb$ coupling
- Search for new physics

($4th$ gen., $H+$, $W'$ ...)

<table>
<thead>
<tr>
<th></th>
<th>Tevatron [pb] $\sqrt{s}=1.96$ TeV</th>
<th>LHC [pb] $\sqrt{s}=7$ TeV</th>
<th>LHC [pb] $\sqrt{s}=10$ TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>s-channel</td>
<td>1.0</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>t-channel</td>
<td>2.2</td>
<td>65</td>
<td>124</td>
</tr>
<tr>
<td>associated production</td>
<td>0.26</td>
<td>11</td>
<td>29</td>
</tr>
</tbody>
</table>

1) PRD 74, 114012 (2006)
2) values scaled to 10 TeV based on PRD 70, 114012 (2004); Nucl. Phys. B726, 109 (2005)
3) JHEP 0910, 042 (2009)

Discovered spring 2009

t-channel:

- Biggest cross section
- Improved S/B ratio compared to Tevatron
- Most promising for re-discovery
**Signal and Background**

**Signal:**
Single top t-channel events, where the W decays leptonically into a muon and a neutrino.

**Important backgrounds:**

<table>
<thead>
<tr>
<th>Process</th>
<th>$\sigma \times \text{BR} \ [\text{pb}]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>single top, t channel ($W \rightarrow l\nu$)</td>
<td>42.9</td>
</tr>
<tr>
<td>single top, s channel ($W \rightarrow l\nu$)</td>
<td>1.6</td>
</tr>
<tr>
<td>single top, tW</td>
<td>29</td>
</tr>
<tr>
<td>top pair</td>
<td>414</td>
</tr>
<tr>
<td>$W/Z+$ jets ($W/Z \rightarrow$ leptons)</td>
<td>45,480</td>
</tr>
<tr>
<td>$WW, WZ, ZZ$</td>
<td>117</td>
</tr>
<tr>
<td>QCD ($\mu$ enriched)</td>
<td>121,700</td>
</tr>
</tbody>
</table>

$\sqrt{s}=10\text{TeV}$
Signal and Background Modeling

Signal modeling (t-channel):
- MadGraph + Pythia for showering
- W-b and W-g fusion processes generated separately and matched in $p_T$ of $2^{\text{rd}}$ b to match NLO calc. ($ZTOP$)

\begin{center}
\begin{tikzpicture}[baseline=(current bounding box.center),thick]
\node (u) at (0,0) {$u$};
\node (d) at (1,0) {$d$};
\node (W) at (0.5,0.5) {$W^+$};
\node (t) at (0.5,-0.5) {$t$};
\node (b) at (0.5,-1) {$b$};
\node (V) at (0,0) {$V_{tb}$};
\draw (u) -- (W); \draw (W) -- (t); \draw (t) -- (b);
\end{tikzpicture}
\hspace{1cm}
\begin{tikzpicture}[baseline=(current bounding box.center),thick]
\node (u) at (0,0) {$u$};
\node (d) at (1,0) {$d$};
\node (W) at (0.5,0.5) {$W^+$};
\node (t) at (0.5,-0.5) {$t$};
\node (b) at (0.5,-1) {$b$};
\node (V) at (0,0) {$V_{tb}$};
\draw (u) -- (W); \draw (W) -- (t); \draw (t) -- (b);
\end{tikzpicture}
\end{center}

W-b fusion

W-g fusion

Background modeling:
- Single top s-channel and tW-channel: MadGraph + Pythia for showering
- tt+jets, W/Z+jets: MadGraph + Pythia for showering
- WW/WZ/ZZ, multi-jet QCD ($\mu$ enriched): Pythia

Use of MC@NLO samples for tW-channel is planned
Event Selection – Muon, Jets

- **Trigger:** muon trigger \((p_T > 15 \text{ GeV})\)

- **Single isolated muon** \((p_T > 20 \text{ GeV}, |\eta| < 2.1)\)

\[
relIso = \frac{p_{T,\mu}}{p_{T,\mu} + tkIso + caloIso} > 0.95
\]

\(tkIso (caloIso):\) Scalar sum of \(p_T(E_T)\) of tracks (cal. deposits) in a cone of \(\Delta R=0.3\) around \(\mu\)

- **Reduction of QCD by a factor \(\approx 50\)**

- **Exactly 2 jets, far from the muon**

  *Iterative Cone algorithm* \((R=0.5), p_T^{\text{calib}} > 30 \text{ GeV}, |\eta| < 5, \Delta R(\mu, \text{jets}) > 0.3\)

  Calib: calibrated jets; scaled with factor that describes detector response depending on jet \(E_T\) and \(\eta\)

\[\sqrt{s}=10\text{ TeV}\]
Event Selection - b-tagging

Track counting algorithm (TC):

Impact parameter significance (IPsig) of track in jet with second (high eff.) and third highest (high purity) IPsig

- Exactly 1 jet, tagged as b-jet by the TC high purity algorithm
  - Reduction of $W/Z+\text{light}$ events by 3 orders of magnitude

- Veto events with a 2$^{\text{nd}}$ jet tagged as b-jet by TC high efficiency algorithm
  - Reduction of top pair events

Use of a more sophisticated b-tagger is planned
Cut to Further Reduce QCD

Transverse mass of $W$ boson ($t\rightarrow Wb$)

$$M_T = \sqrt{(p_{T,\mu} + p_{T,\nu})^2 - (p_{x,\mu} + p_{x,\nu})^2 - (p_{y,\mu} + p_{y,\nu})^2} > 50\text{GeV}/c^2$$

- $W+$jets events: real $\mu$'s from $W$-boson → Jacobian peak
- QCD events: $\mu$'s from $B/C$-hadrons, and decay in flights, punch-through
### Expected Event Yield

<table>
<thead>
<tr>
<th>Process</th>
<th>Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>single top, t channel (W→lv)</td>
<td>102</td>
</tr>
<tr>
<td>single top, s channel (W→lv)</td>
<td>1.8</td>
</tr>
<tr>
<td>single top, tW</td>
<td>22.3</td>
</tr>
<tr>
<td>top pair</td>
<td>136</td>
</tr>
<tr>
<td>W/Z + jets (W/Z→leptons)</td>
<td>55</td>
</tr>
<tr>
<td>WW, WZ, ZZ</td>
<td>2.3</td>
</tr>
<tr>
<td>QCD (μ enriched)</td>
<td>12</td>
</tr>
<tr>
<td>total background (B)</td>
<td>229</td>
</tr>
</tbody>
</table>

\[ \sqrt{s}=10\text{TeV}, \, L=200\text{pb}^{-1} \]

- \(42.2\%\) \(\text{ttbar}\)
- \(31.7\%\) \(\text{Signal}\)
- \(6.8\%\) \(\text{tW}\)
- \(3.7\%\) \(\text{QCD}\)
- \(15.5\%\) \(W+x\)

\[ \sqrt{s}=7\text{TeV} \]

Similar S/B expected, but with slightly smaller top pair fraction.

- Expected background uncertainties at the level of (30-50)%
- Sensitivity of simple counting experiment too small
**QCD Background Estimation**

**QCD rate:** Determine number of QCD events in signal region by performing a fit to the \( M_T \) distribution (*data-driven method*)

\[
Fit \ function: a \cdot S(M_T) + b \cdot B(M_T)
\]

Parametrizations for signal-like processes (S) and for QCD (B) are obtained from:

- **Signal-like:**
  - \( Z+\text{jets} \) sample (+ \( M_W/M_Z \)- rescaling, take one \( \mu \) as \( \nu \))

- **QCD background:**
  - Sample without b-tag requirement and anti-isolation cut

Uncertainty (syst.+stat.): \( \pm 45\% \)
Reconstruction of Single Top Events

W boson reconstruction:

W mass constraint → 2\textsuperscript{rd} order equation in \( p_{z,\nu} \)

- Complex solutions (36%) 
  → Varying \( p_{x,\nu}, p_{y,\nu} \) so that \( M_T=M_W \rightarrow \text{Im}(p_{z,\nu})=0 \)

- Two real solutions (64%) 
  → Pick the one with smallest \( |p_{z,\nu}| \)

Assigning the b quark from the top quark decay:

Take the b-tagged jet 
→ Correct in 92.2%, only in 4% the 2\textsuperscript{nd} b is chosen
Polarization of the Top Quark

Single top s- and t-channel events:
Polarization of the top quark
\textit{(due to V-A nature of Wtb coupling)}
→ passed to its decay particles

Sensitive variable: $\cos \Theta^*_lj$

\textbf{Signal:} linear dependence on $\cos \Theta^*_lj$ \textit{(gen. level)}

\textbf{Backgrounds:} flat in $\cos \Theta^*_lj$

\(\sqrt{s}=10\text{TeV}\)

See also PRD 80, 074015 (2009)
Result of $\sqrt{s}=10\text{TeV}$ Study

Binned likelihood fit to $\cos\theta_{ij}^*$:

- Fit range: $[-1, \frac{3}{4}]$
- Take single top template from MC, assume flat template for sum of backgrounds
- No assumption about background size

Ensemble tests:

- Determine uncertainty on cross section and expected sensitivity (*hypothesis test*)

$\cos\theta_{ij}^*$ is very robust against sources of uncertainty

(Extreme bkg shapes: $2.7\sigma \rightarrow 2.6\sigma$)
**Single Top Prospects**

\[ \sqrt{s} = 10\text{TeV} \]

**Graph:***

- **CMS Preliminary**
- **x-axis:** *exp. sensitivity [\sigma]*
- **y-axis:** *cos\(\Theta^*_ij\)*
- **Labels:**
  - **x-lim:** 200 to 700
  - **y-lim:** 2 to 6

**Table:**

<table>
<thead>
<tr>
<th>Process</th>
<th>(\sigma_{7\text{TeV}} / \sigma_{10\text{TeV}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>t channel</td>
<td>0.48</td>
</tr>
<tr>
<td>s channel</td>
<td>0.92</td>
</tr>
<tr>
<td>tW</td>
<td>0.37</td>
</tr>
<tr>
<td>top pair</td>
<td>0.43</td>
</tr>
<tr>
<td>W + jets</td>
<td>0.65</td>
</tr>
<tr>
<td>QCD ((\mu) enriched)</td>
<td>0.58</td>
</tr>
</tbody>
</table>

- **Rescaling**: \(\sqrt{s} = 7\text{TeV}\) \(\approx \sqrt{s} = 7\text{TeV}\)

**Text:**

- **Analysis @ 7TeV:**
  - To obtain the same exp. sensitivity as in the 10TeV study, about a factor 2 more int. luminosity is needed.

DIS 2010, Florence, 20.4.2010

Jeannine Wagner-Kuhr
Summary

Early single top analysis - fit $\cos \theta_{lj}^*$:
(muon-jet angle in rec. top quark rest frame)

- Robust against systematics

- Evidence of single top production at 1/fb @7 TeV seems to be well in reach

With ongoing improvements a rediscovery of single top production at 1/fb @7 TeV seems to be likely

(eg. inclusion of electron channel, use of more sophisticated b-tagger and/or combination of several variables)