Single top: prospects at LHC

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Outline

• What changes between Tevatron and LHC
• Overview of single top quark at LHC
• Searches at CMS, mostly O(10fb$^{-1}$) and early searches at ATLAS, mostly O(1fb$^{-1}$)
• Conclusions
LHC is good for searches

- High luminosity: gathering $O(10\text{fb}^{-1})$ should be easy, once we start.
- High energy: larger signal cross sections (and not so larger background ones)

| Process                      | $\sigma$(Tevatron)   | $\sigma$(LHC)    |
|------------------------------|----------------------|------------------|
| ttbar pairs                  | $6.70^{+0.71}_{-0.88}$ pb | $825\pm150$ pb   |
| single top, s-ch.            | $0.88\pm0.12$ pb     | $10\pm1$ pb      |
| single top, t-ch.            | $1.98\pm0.22$ pb     | $245\pm17$ pb    |
| tW production                | $0.15\pm0.04$ pb     | $60\pm10$ pb     |
| Wjj (*)                      | $\sim1200$ pb        | $\sim7500$ pb    |
| bb+jets (*)                  | $\sim2.4\times10^5$ pb | $\sim5\times10^5$ pb |

(*) hep-ph/9806332: after selection cuts to mimic top signals

$\sigma$(Tevatron) \div \sigma$(LHC):
- $ttbar$ pairs: $(x120)$
- Single top, s-ch.: $(x10)$
- Single top, t-ch.: $(x120)$
- tW production: $(x400)$
- Wjj: $(x6)$
- bb+jets: $(x2)$
LHC is bad for systematics

- Rejection of backgrounds depends on observables not easy to control at startup:
  - **jet counting**: uncertainties on JES knowledge, extra jets from radiation, pile up or detector noise
  - **b-tagging**: knowledge of its performance with a misaligned detector
  - **MET**: controlling the detector resolution for a small true missing energy (~40GeV) in multi-jet events (none of these comes for free from Z->μμ/ee)
- Because of this, single top can be easy to see but very hard to measure accurately
Overview at LHC

- The cross section hierarchy is different at LHC

\[ \sigma_{t-channel} = 240 \text{pb} \]
\[ \sigma_{tW \text{ production}} = 60 \text{pb} \]
\[ \sigma_{s-channel} = 10 \text{pb} \]

- Only decays with at least one \( \text{e/\mu} \) in the final state will be usable at the beginning
Overview at LHC

• Taking into account the BR, not summing on flavours the cross sections become
  
  - t-ch \((qt \rightarrow qbW \rightarrow qb\ell\nu)\) \(\sigma \cdot BR = 26pb\) (x2)
  - tW/1\(\ell\) \((tW \rightarrow bWW \rightarrow bqq'\ell\nu)\) \(\sigma \cdot BR = 4pb\) (x2)
  - tW/2\(\ell\) \((tW \rightarrow bWW \rightarrow b\ell\nu\ell'\nu')\) \(\sigma \cdot BR = 0.74pb\) (x4)
  - s-ch \((bt \rightarrow bbW \rightarrow bb\ell\nu)\) \(\sigma \cdot BR = 1.1pb\) (x2)
Studies at CMS

• All the four possible final states have been studied for the Physics TDR \cite{CERN/LHCC-2006-021}

• The basic assumptions were:
  – 10fb$^{-1}$ integrated luminosity, with the \textquotedblright 2\cdot10^{33}\textquotedblright pileup
  – Ideal alignment, calibrations with 10fb$^{-1}$ of data
  – Keeping the analysis simple: extract only $\sigma$, as a counting experiment, no multivariate methods
  – Generators: SingleTop and TopRex for signal, TopRex, Alpgen and Pythia for the backgrounds.
  – Use of full GEANT4 simulation when possible, or the fast but fairly accurate FAMOS simulation
Studies at ATLAS

- CSC notes will be public ~July, all results shown here are thus preliminary
- The three channels are considered in the final states with exactly one lepton (electron or muon)
- Studies based on:
  - $1\text{fb}^{-1}$ integrated luminosity, with no pileup
  - Realistic detector and misalignment
  - Cut-and-count analysis as a baseline; multivariate methods in addition for better background rejection
  - Generators: AcerMC for signal, MC@NLO, AlpGen and Pythia for backgrounds
  - Use of full GEANT4 simulation
ATLAS common preselection

• Similar features in the three channels → common preselection to reduce backgrounds (ttbar, W+jets and QCD)
  – Exactly one isolated high $p_T$ lepton
  – 2-4 jets, one of which is tagged as a b-jet
  – MET > 20 GeV

• Single-top efficiency
  – 9-10% (electrons)
  – 10-12% (muons)

• Rejection of W+jets $O(10^4)$, ttbar $O(20)$
ATLAS: t-channel

- Cut-and-count analysis with simple kinematic cuts
  - $p_t$ (b-jet) > 50 GeV (against W+jets)
  - Hardest light jet $|\eta| > 2.5$ (against ttbar)
ATLAS: t-channel sensitivity

- Results for sequential cut analysis
- Significant reduction wrt to ATLAS TDR (1999)
- Difference understood in terms of
  - Pythia new parton shower algorithm
  - ME: Pythia $\rightarrow$ AcerMC
  - W+jets: Herwig $\rightarrow$ Alpgen
  - tt dileptonic and tt with $\tau$ were neglected

| Process               | Efficiency | N (1 fb$^{-1}$) |
|-----------------------|------------|-----------------|
| t-channel ($\mu$ or $e$) | 1.8%       | 1460            |
| tt (l+jets)           | 0.6%       | 1560            |
| tt with $\tau$        | 0.4%       | 740             |
| tt (dilepton)         | 1.3%       | 520             |
| W+jets                | 0.0017%    | 870             |
| Wbb+jets              | 0.4%       | 70              |
| S/B                   |            | 0.37            |
ATLAS: t-channel BDT

- MV analysis to suppress ttbar background
- Boosted Decision Trees (BDT) applied after selection (except $\eta$ cut)
- 40 object/event level variables considered
- Reduce to sets that are less sensitive to JES, e.g.
  - $p_T$ and $\cos(\theta^*)$ of leading jet
  - $p_T$ and $\eta$ of leading non-b jets
  - centrality($j_1$, $j_2$), $H_T(j_1,j_2,\text{MET},\ell)$, $M_T(W)$
  - $\Delta R(j_1,j_2)$, $\Delta R(j_1,\text{lep})$, $\Delta R(j_1\text{non-b},\ell)$
  - $\eta$ (max), #jets
ATLAS: t-channel BDT result

- BDT cut optimised for cross-section uncertainty including systematic effects
  - $S/B = 1.3$ (542 events)
  - 5.7% (stat), 22.4% (total uncert.)

Reco’d top mass after D cut
**ATLAS: t-channel systematics**

- **Experimental:** b-tagging, jet energy scale
- **Theoretical/MC:** ISR/FSR, PDF, MC model

| source          | Cuts $\Delta \sigma/\sigma$ | BDT $\Delta \sigma/\sigma$ | source          | Cuts $\Delta \sigma/\sigma$ | BDT $\Delta \sigma/\sigma$ |
|-----------------|-----------------------------|----------------------------|-----------------|-----------------------------|----------------------------|
| MC stat         | 6.5%                        | 7.9%                       | Bckgnd normal. | 22.9%                       | 8.2%                       |
| lumi 5%         | 18.3%                       | 8.8%                       | PDF             | 12.3%                       | 2.6%                       |
| b-tag 5%        | 18.1%                       | 6.6%                       | Lepton ID       | 1.5%                        | 0.7%                       |
| JES 5%          | 21.6%                       | 9.9%                       | MC model        | 4.2%                        | 4.2%                       |
| ISR/FSR         | 9.8%                        | 9.4%                       | Total systematic| 44.7%                       | 22.4%                      |
| Data stat       |                             |                            |                 | 5.0%                        | 5.7%                       |

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CMS, t-channel

- Analysis performed only in the $W\rightarrow \mu\nu$ channel
- 1 muon, 1 b-tagged jet, 1 forward jet, $E_T^{\text{miss}}$
- Cuts on $M_T(W)$, $M(\text{top})$, $|\Sigma_T| = E_T(\mu+b+j+E_T^{\text{miss}})$

### Expected events

| Process      | N/10fb$^{-1}$ |
|--------------|---------------|
| Signal       | 2389          |
| t tbar       | 1189          |
| Wbb+jet      | 195           |
| W+jet        | 102           |

$S/B \sim 1.4$

[CMS NOTE 2006-084; CMS Physics TDR II, sect. 8.4.2]
CMS: t-channel, results

Uncertainties on S and B for 10fb$^{-1}$, and their impact on the cross section measurement

|             | signal | ttbar | Wbbj | Wjj | $\Delta\sigma/\sigma$ |
|-------------|--------|-------|------|-----|----------------------|
| **Statistics** | 2.0%   | 2.9%  | 7.2% | 4.9%| 2.7%                 |
| **Theory**   | 4.0%   | 5.0%  | 17.0%| 5.0%| 5.0%                 |
| **JES (5-2.5%)** | 3.0%   | 6.1%  | 3.1% | <1% | 4.3%                 |
| **B-tagging** | 4.0%   | 4.0%  | 4.0% | 4.0%| 4.5%                 |
| **Luminosity** | 5.0%   | 5.0%  | 5.0% | 5.0%| 8.7%                 |

("theory" includes PDFs, $m_t$, $m_b$, $\Lambda_{\text{QCD}}$, $\sigma_{\text{background}}$)

$$\Delta\sigma/\sigma = 2.7\%^{\text{(stat)}} + 8\%^{\text{(syst)}} + 8.7\%^{\text{(lumi)}}$$
tW production

- The final state is very similar to ttbar production, except for one less b-jet: jet counting is critical
  - CMS: Jets from calorimeter noise were vetoed by using information from tracks and calo tower distribution
  - ATLAS: b-tag veto, analysis adapted according to #jets
- Can't achieve a good S/B, so background normalization from data important to avoid large systematic uncertainties
  - Background-like sample dominated by ttbar selected with cuts very similar to the ones for signal, to cancel out systematics on background subtraction
CMS: tW dileptonic

- In the e+µ channel, to avoid Z background
- Select events with 1 or 2 jets, classify by the $P_T$ of the second jet (if any) and the number of b-tags.
- Signal selected as 1 b-jet, background control as 2 b-jet
CMS: tW semi-leptonic

- Events are selected requiring exactly one lepton (e,\(\mu\)), 1 b-jet and two light quark jets, and some MET (to control QCD background)

- (W,b) pairing from a Fisher discriminant using \(P_T(b+W), \Delta R(W,b)\) and \(q(b) \cdot q(W)\) from jet charge
CMS: tW summary

Expected events [10fb$^{-1}$]

- **Semi-leptonic (S/B~0.2)**
  - signal: 1700
  - ttbar: 7624
  - W+jets: 759
  - t-ch top: 351

- **Di-leptonic (S/B~0.37)**
  - signal: 562
  - ttbar: 1433
  - WW+jets: 55

$\Delta \sigma/\sigma$ expected 10fb$^{-1}$

| Source                  | 1L  | 2L  |
|-------------------------|-----|-----|
| Statistics              | 7.5%| 8.8%|
| Luminosity              | 7.8%| 5.4%|
| Jet E.S.                | 9.4%| 20% |
| b-tagging               | 3.6%| 8.7%|
| PDF                     | 1.6%| 6.0%|
| Pileup                  | 10% | 6.1%|
| **TOTAL**               | 19% | 25% |

[CMS NOTE 2006-086; CMS Physics TDR II, sect. 8.4.2]
ATLAS: tW cut-and-count

- Only semi-leptonic final state considered
- Analysis divided according to #jets in final state
- 1 b-tagged jet with $p_T > 50$ GeV, veto second b-jet to optimally reject ttbar (main concern)
- W window cut for events with $>3$ jets

| Events in 1 fb$^{-1}$ | 1b+1jet | 1b+2jets | 1b+3jets |
|------------------------|---------|----------|----------|
| tW channel             | 435     | 164      | 40       |
| other single top       | 1260    | 99       | 58       |
| ttbar                  | 1980    | 770      | 274      |
| W(bb)+jets             | 3075    | 220      | 44       |
| S/B                    | 6.8%    | 15%      | 10.6%    |

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ATLAS: tW BDT

• for each background
  – ttbar 1l, 2l, W(bb)+jets, t-channel
• and each jet multiplicity a boosted decision tree function is defined $\rightarrow$12 BDTs (e and $\mu$ together)
• pool of 25 discriminating variables identified
  – Opening angles(6), $p_T$(3), $\eta$(2), $\cos\Delta\phi$
  – Invariant (transverse) masses (6), f(MET), $H_T$(2)
  – $p_z$(neutrino)
  – sphericity, aplanarity, centrality
• minimize uncertainty on $\sigma$ including syst. uncert.
ATLAS: tW results

- S/B ratios in the 3 classes
  - 35%, 45%, 16% (86 ev. sel.)
- 3σ evidence with few fb⁻¹
- 20% uncertainty with 10 fb⁻¹

| Source       | 1 fb⁻¹ | 10 fb⁻¹ |
|--------------|--------|---------|
| Var          |        |         |
| Δσ/σ         |        |         |
| MC stat      | 15.6%  |         |
| Lumi         | 5%     | 20%     |
| Bckgnd σ     | 10%    | 23.4%   |
| ISR/FSR      | 9%     | 24.0%   |
| PDF          | 2%     | 5.2%    |
| b-fragm.     | 3.6%   | 9.4%    |
| data stat.   | 20.6%  | 6.6%    |
| Total uncert. | 52%   | 20.5%   |
CMS: s-channel

- Much harder at LHC than at Tevatron as the relative cross section is much smaller.

- Selection requirements:
  - one isolated lepton (e, µ)
  - exactly two jets, both b-tagged
  - missing $E_T$
  - cuts on $M_T(W)$, $M(t)$, $P_T(t)$, $\Sigma_T$, $H_T$

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[CMS NOTE 2006-084; CMS Physics TDR II, sect. 8.4.4]
CMS: s-channel

- Two control samples selected to constraint ttbar background (semi-leptonic and di-leptonic)

- **Expected events** [10fb$^{-1}$] (S/B ~ 0.13)
  
  - signal: 273
  - ttbar: 1260
  - t-channel: 630
  - Wbb: 155

- **Uncertainty on $\sigma$** [10fb$^{-1}$]
  
  $\Delta\sigma/\sigma = 18\%$ (stat) + 31\% (syst) + 19\% (lumi)
  
  dominated by the systematics on the ttbar semi-leptonic background normalization from JES

[CMS NOTE 2006-084; CMS Physics TDR II, sect. 8.4.4]
ATLAS: s-channel

- Require exactly two b jets, veto any further jet
- Pure cut-and-count analysis not possible
  - S/B 10%, 25 selected events
- Define 5 likelihood functions for background categories (3 ttbar, W+jets, t-channel)
- Discriminating variables
  - see tW channel
  - $\Delta \eta$, $p_T$(top)
  - choose only most significant
ATLAS: s-channel likelihood

- S/B improves to 19% (15ev)
- ISR/FSR radiation and b-tagging critical

| Source         | 1 fb⁻¹ | 10 fb⁻¹ |
|----------------|--------|---------|
|                | Var    | Δσ/σ    | Var    | Δσ/σ    |
| MC stat        | 29%    |         |         |         |
| Lumi           | 5%     | 31%     | 3%      | 18%     |
| b-tagging      | 5%     | 44%     | 3%      | 25%     |
| JES            | 5%     | 25%     | 1%      | 5%      |
| lepton ID      | 1%     | 6%      | 1%      | 6%      |
| Bckgnd σ       | 10%    | 47%     | 3%      | 16%     |
| ISR/FSR        | 9%     | 52%     | 3%      | 17%     |
| PDF            | 2%     | 16%     | 2%      | 16%     |
| b-fragm.       | 3.6%   | 19%     | 3.6%    | 19%     |
| data stat.     | 64%    | 20%     |         |         |
| Total          | 115%   | 52%     |         |         |

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ATLAS: QCD rejection

- Observation (e.g. D0): fake MET aligned with lepton → triangular cut in $\Delta \phi$ vs. MET plane
- Fake lepton rate will be determined from data
  - e.g. $m_T(W) < 50$GeV extrapolated to signal region
  - assume QCD background fully under control
CMS: QCD background estimation

- Due to the huge cross section, the background from QCD multi-jet could only be estimated indirectly, using the cut factorization method:
  - The first steps of the selection were grouped into some sets of approximately independent cut sets, for which the efficiency was extracted from QCD simulations
  - The combined efficiency was taken as product of the efficiencies of all the cut sets
  - An upper limit to the efficiency of the later steps of the selection on QCD was taken using the signal efficiency

- The estimated background is very small except for tW semi-leptonic analysis, for which \( B_{QCD}/S \sim 30\% \).
Conclusions

- All channels with leptons have been studied
- t-channel
  - CMS: PhysTDR study gives >5σ observation for 10 fb\(^{-1}\) (naïve rescaling of statistical and systematic uncertainties hints that even 1 fb\(^{-1}\) might be ok)
  - ATLAS: two studies shown for 1 fb\(^{-1}\)
- tW channel should be visible with O(10 fb\(^{-1}\))
- s-channel might be visible with O(10 fb\(^{-1}\)), but it will be hard due to poor S/B ratio
Backup
ATLAS: Effect of pile-up

- With a luminosity of $10^{32}$ cm$^{-2}$s$^{-1}$ we estimate the relative efficiency for signal and background.
- Pile-up modeling will be tuned with data.
- Uncertainty is expected to become negligible with respect to other sources.
- No systematic uncertainty considered here.

| Channel  | rel. $\varepsilon$(signal) | rel. $\varepsilon$(ttbar) |
|----------|-----------------------------|---------------------------|
| t        | 75%                         | 66%                       |
| tW (2jets) | 82%                       | 84%                       |
| tW (3jets) | 53%                       | 61%                       |
| tW (4jets) | 74%                       | 80%                       |
| s        | 91%                         | 85%                       |
ATLAS: Results summary

| Analysis          | Stat 1fb⁻¹ | Syst 1fb⁻¹ | Stat 10fb⁻¹ | Syst 10fb⁻¹ |
|-------------------|------------|------------|-------------|-------------|
| t-channel C&C     | 5.0%       | 44.4%      | 1.6%        | 22.3%       |
| t-channel BDT     | 5.7%       | 21.7%      | 1.8%        | 9.8%        |
| tW-channel BDT    | 20.6%      | 48%        | 6.6%        | 19.4%       |
| s-channel LH      | 64%        | 95%        | 20%         | 48%         |

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ATLAS: triggering on single top

- Inclusive isolated electron and muon triggers
- Overall top quark efficiency 84%
- Preselection requires 30 GeV leptons, well on the trigger efficiency plateau
CMS: triggering on single top

- Single lepton triggers used.
- Full L1 and HLT simulation included in the analysis.
- Combined L1*HLT efficiency
  - ~50% for channels with a single lepton
  - ~70% for tW di-leptonic
  (note: $W \rightarrow \tau \nu$ are included)
CMS, t-channel: selection

- Selection cuts ($W \rightarrow \mu\nu$ only):
  - 1 muon, $P_T > 19$ GeV, $|\eta| < 2.1$
  - 1 b-jet, $P_T > 35$ GeV, $|\eta| < 2.5$, $b$-discr > 2.4
    (b-tag cut giving $\epsilon_b \sim 50\%$, $\epsilon_{uds} \sim 0.3\%$)
  - 1 forward jet ($P_T >$ GeV, $|\eta| < 2.5$)
  - $E_T^{\text{miss}} > 40$ GeV
  - $|\Sigma_T| < 43.5$ GeV ($\Sigma_T = \vec{p}_T(\mu) + \vec{E}_T(b) + \vec{E}_T(j) + \vec{E}_T^{\text{miss}}$)
  - $m_T(W)$ within [50, 120] GeV
  - $m(t)$ within [50, 120] GeV
CMS: t-channel, plots

| Process     | N^{expected}/10fb^{-1} |
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