First observation of single top production in association with a W boson in pp collisions at 8 TeV by the CMS experiment

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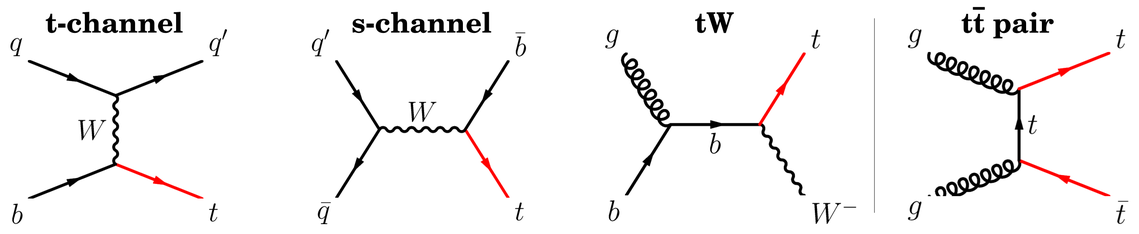
Single Top at the LHC

Top quarks can be produced singly (through the electroweak interaction via three production channels) or in pairs:

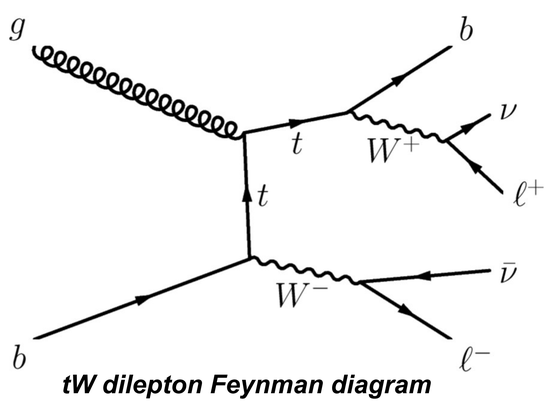


σ(pb)	t-channel	s-channel	tW channel	$t\bar{t}$
Tevatron: $p\bar{p}$ @ 1.96 TeV	2.08	1.05	**0.22**	7.08
LHC: pp @ 7 TeV	65.9	4.56	**15.6**	163
LHC: pp @ 8 TeV	87.2	5.55	**22.2**	245.8

Cross sections for single top and top pair production at the LHC and Tevatron

This analysis studies the production of a single top quark in association with a W boson (tW). Evidence for this process was seen by both ATLAS[1] and CMS[2] using 7 TeV data. This analysis uses data collected by the CMS experiment at a center of mass energy of 8 TeV, corresponding to an integrated luminosity of 12.2 fb^{-1}.

Event Selection



tW dilepton Feynman diagram

Top quark decays almost exclusively to a b quark and a W boson. In the dilepton final state, both W bosons decay into a lepton (e or μ) and a neutrino.

Final State:

- b-jet from top quark decay
- Two oppositely charged leptons (**eμ**,**μμ**,**ee**)
- E_T^{miss} from neutrinos

Lepton Selection:

- Transverse momentum p_T > 20 GeV
- Pseudorapidity |η| < 2.4 (2.5) for muons (electrons)
- Isolated from other particles
- Oppositely Charged

Jet Selection:

- Anti-k_t algorithm
- Transverse momentum p_T > 30 GeV
- Pseudorapidity |η| < 2.4
- Tagged as coming from a b quark (b-tagged) based on combined secondary vertex tagger

Additional Cuts:

- Invariant Mass of leptons, $m_{\ell\ell}$ > 20 GeV
- Veto event 81 < $m_{\ell\ell}$ < 101 GeV in μμ and ee channels
- E^T_{miss} > 30 GeV in μμ and ee channels

Signal / Control Regions:

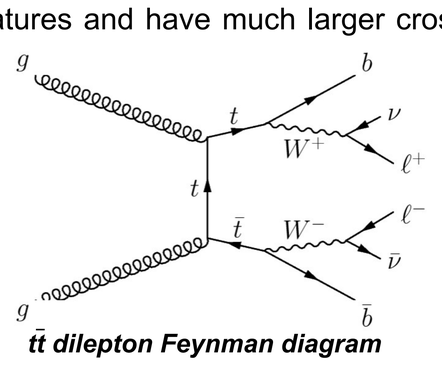
- Signal and control regions based on jet and b-tagged jet multiplicity
- Signal region:
  - One jet, which is b-tagged (one jet – one tag : 1j1t)
- Control regions:
  - 2 jets, 1 b-tag (2j1t)
  - 2 jets, 2 b-tags (2j2t)

Backgrounds

Numerous processes provide similar event signatures and have much larger cross sections:

- $t\bar{t}$
- Z+jets
- Diboson WW/WZ/ZZ
- Single top

The most significant background is by far $t\bar{t}$, the difference is only a matter of one b-jet at LO.



$t\bar{t}$ dilepton Feynman diagram

	1j1t	2j1t	2j2t
tW	1500±20±130	790±20±80	220±10±30
$t\bar{t}$	7090±60±900	12910±80±1320	7650±60±1020
Z/γ^*, other	670±30±90	370±30±60	36±7±12
Tot. sim.	9260±70±1040	14070±90±1410	7910±70±1020
Data	9353	13479	7615

Number of events passing event selection for simulation and data for all three dilepton channels combined. Statistical (first) and systematic (second) uncertainties are quoted for simulation estimates

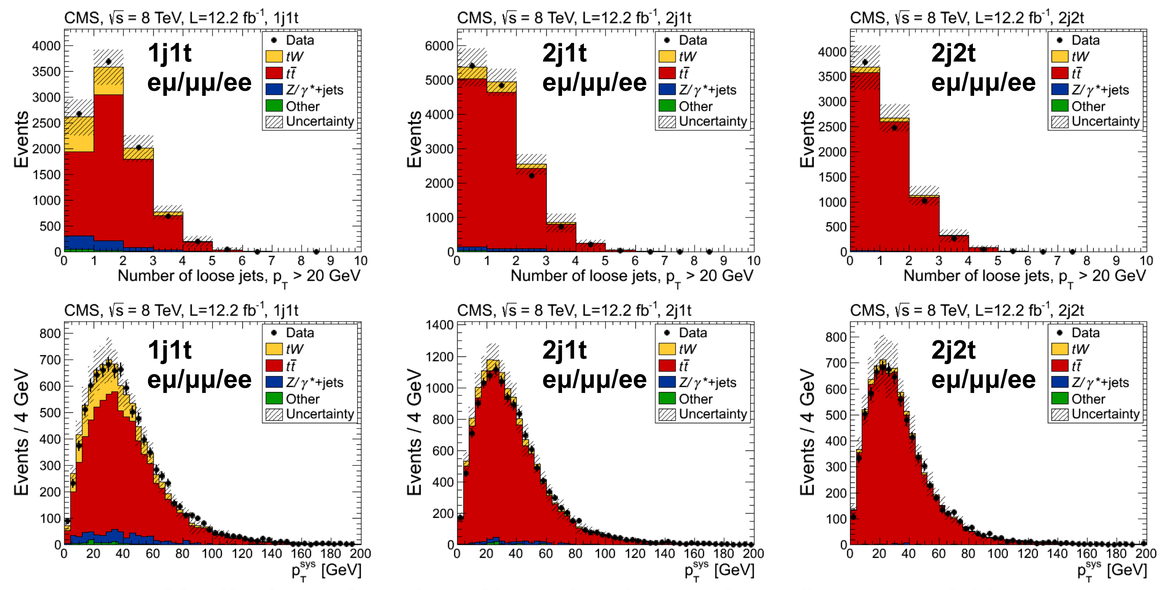
Multivariate Analysis

After event selection a Boosted Decision Tree (BDT) was trained to discriminate between the tW signal and $t\bar{t}$ background, using the input variables:

Input variables selected based on discrimination power as well as agreement in data and MC.

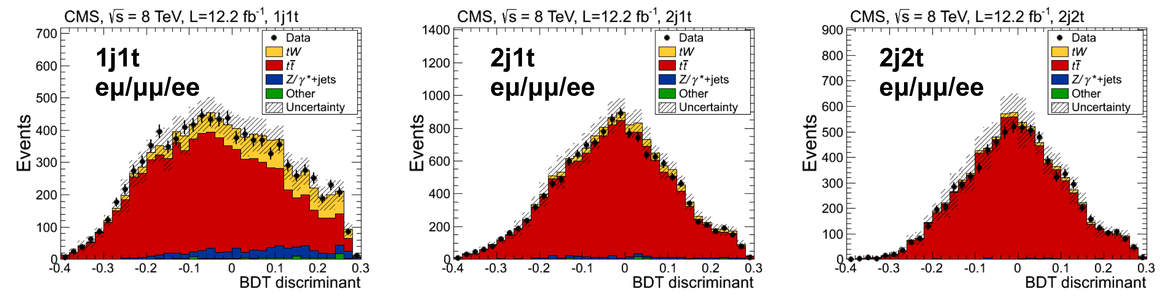
Trained on 200k signal and background MC events.

Variable Name	Description
# of loose jets	Number of loose jets, $p_T > 20$ GeV, $\|\eta\| < 4.9$
# of central loose jets	Number of loose jets, $p_T > 20$ GeV, $\|\eta\| < 2.4$
# of b-tagged loose jets	Number of loose jets, $p_T > 20$ GeV, q_b-tagged, $\|\eta\| < 2.4$
p_T^{sys}	Vector sum of p_T of leptons, jet, and E_T^{miss}
H_T	Scalar sum of p_T of leptons, jet, and E_T^{miss}
p_T(jet)	p_T of the leading, tight, b-tagged jet
p_T(loose jet)	p_T of leading loose jet, defined as 0 for events with no loose jet present
p_T^{sys}/H_T	Ratio of p_T^{sys} to H_T for the event
m_{sys}	Invariant mass of the combination of the leptons, jet, and E_T^{miss}
Centrality(jℓℓ)	Centrality of jet and leptons, defined as ratio of transverse to total energy
p_T(leptons)/H_T	Ratio of scalar sum of p_T of the leptons to the H_T of full system
p_T(jℓℓ)	Vector sum of p_T of jet and leptons
E_T^{miss}	Missing transverse energy in the event



Distributions of number of loose jets (top) and p_T^{sys} (bottom) variables in the 1j1t, 2j1t, and 2j2t regions

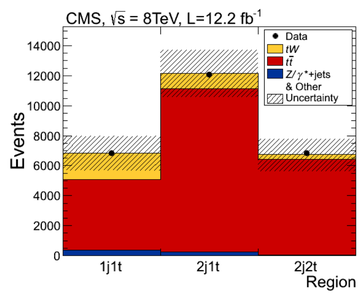
The BDT returns a single discriminant for each event. Signal-like events have a higher value, background-like events get a lower value.



Distributions of BDT discriminant in the 1j1t, 2j1t, and 2j2t regions

A binned likelihood fit to the shape of the BDT discriminant is performed to extract cross section and significance.

- Simultaneous fit to three channels (eμ,μμ,ee) and three regions (1j1t, 2j1t, 2j2t)
- Templates are taken from simulation
- Systematic uncertainties taken into account based on changes to shapes of templates and treated as nuisance parameters



Two cross-check analyses are performed.

- Fit to the distribution of p_T^{sys} variable.
- Fit to event yields

Results

First observation at a significance of at least 5 σ. An excess of events is observed with a probability of 5x10^{-10} of coming from a background-only hypothesis.

Observation with significance of 6.1σ
Expected significance of 5.4 ± 1.4 σ.

Cross section is measured to be **σ = 23.4 ± 5.4 pb**, in agreement with the standard model prediction of σ = 22.2 ± 0.6 ± 1.4 pb[3].

An estimate of the CKM matrix element, $|V_{tb}|$, is extracted under the assumption that $|V_{tb}|$ is much larger than $|V_{td}|$ and $|V_{ts}|$:

$$|V_{tb}| = \sqrt{\frac{\sigma_{tW}}{\sigma_{tW}^{th.}}} = 1.03 \pm 0.12(\text{exp.}) \pm 0.04(\text{th.})$$

Cross-check analyses produce consistent results with those from the BDT analysis:

Fit to p_T^{sys}:	Fit to event yields:
Observed: 4.0 σ ($3.2^{+0.4}_{-0.9}$ σ expected)	Observed: 3.6 σ (2.8±0.9 σ expected)
Cross section: 24±9 pb	Cross section: 33±9 pb

References: [1] Phys. Lett. B 716 (2012) 142
[2] Phys. Rev. Lett. 110, 022003 (2013)
[3]N. Kidonakis,http://arxiv.org/pdf/1210.7813

http://arxiv.org/pdf/1401.2942
Submitted to Phys. Rev. Lett.