

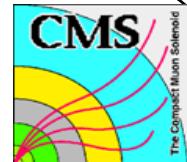
Single top quark production with CMS

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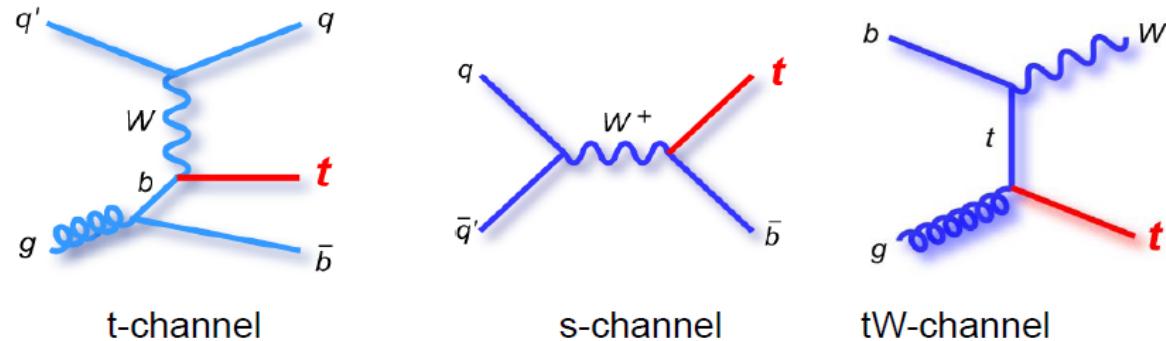
For the
CMS COLLABORATION

Single-top production



- Single top EWK production happens via three main contributions

Kidonakis, NLO+NNLL
 t-channel: PRD 83 (2011) 091503
 s-channel: PRD 81 (2010) 054028
 tW-channel: PRD 82 (2010) 054018

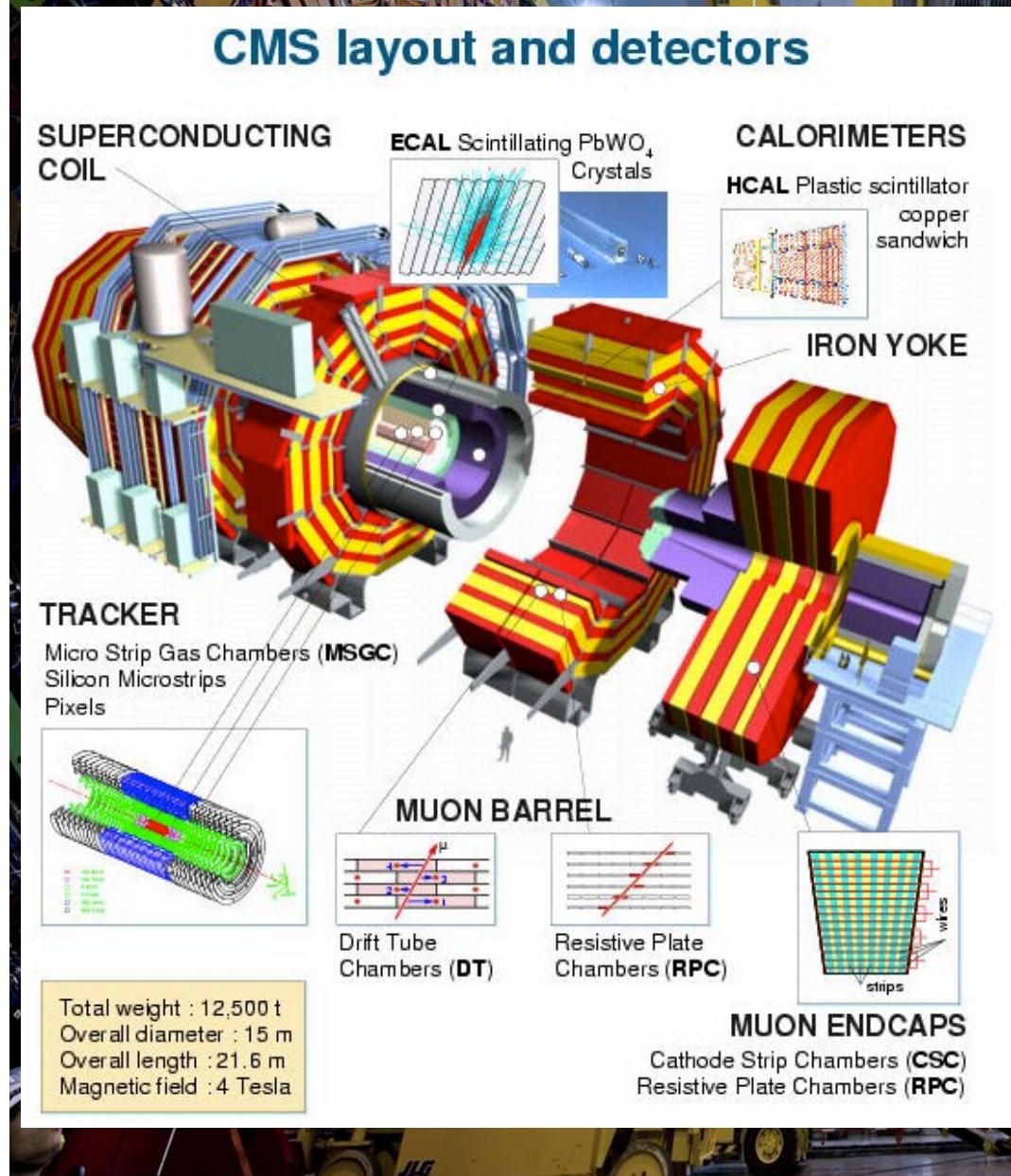


	t channel <i>Phys. Rev. D 83, 091503(R) (2011), N. Kidonakis</i>	s channel <i>Phys. Rev. D 81, 054028 (2010), N. Kidonakis</i>	tW channel <i>Phys. Rev. D 82, 054018 (2010), N. Kidonakis</i>
LHC: $pp @ 7 \text{ TeV}$	64.57 pb	4.59 pb	15.6 pb
Tevatron: $pp @ 1.96 \text{ TeV}$	2.3 pb	1.04 pb	0.22 pb (arxiv.org/pdf/0909.0037)
LHC: $pp @ 8 \text{ TeV}$	87.8 pb	5.6 pb	22.4 pb

Importance of
Single top



- Cross section proportional to $|V_{tb}|^2$, test of unitarity of CKM
- 4th generation?
- Test of b-quark structure function
- Heavy W' , charged H^+
- Anomalous couplings or FCNC in single top production



Physics objects for single-top Analysis

Electrons and Muons

- ✓ High identification efficiency with low fake rate
- ✓ Precise measurement of momentum
- ✓ Isolation to discriminate leptons coming from QCD background
- ✓ Trigger (efficiency + steep turn-on curves)

Jets

- ✓ Measure the energy with low uncertainty of Jet Energy Scale

Missing Transverse Energy (MET)

- ✓ Important to reconstruct neutrino transverse momentum

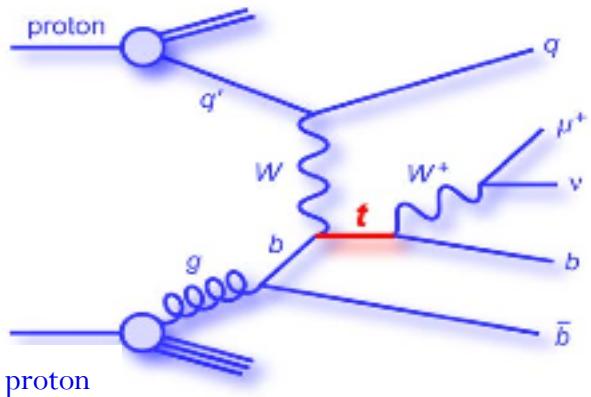
b-jet identification

- ✓ High efficiency in tagging Jets from b quarks
- ✓ Low failure rate in discriminating b jets

t-channel @ 7 TeV



JHEP12(2012)035

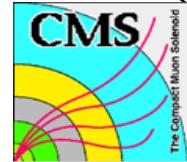


Main Features

- Single isolated lepton (muon or electron)
 - $p_T > 20 \text{ GeV}/c$ $|\eta| < 2.1$ (muon)
 - $p_T > 30 \text{ GeV}/c$ $|\eta| < 2.5$ (electron)
- One central b-jet from top decay
- Additional light-quark jet often in forward region
- Additional b-jet can be present (softer pt)
- Momentum imbalance due to neutrino
 - $m_T > 40 \text{ GeV}/c^2$ (muon)
 - $\cancel{E}_T > 35 \text{ GeV}/c^2$ (electron)

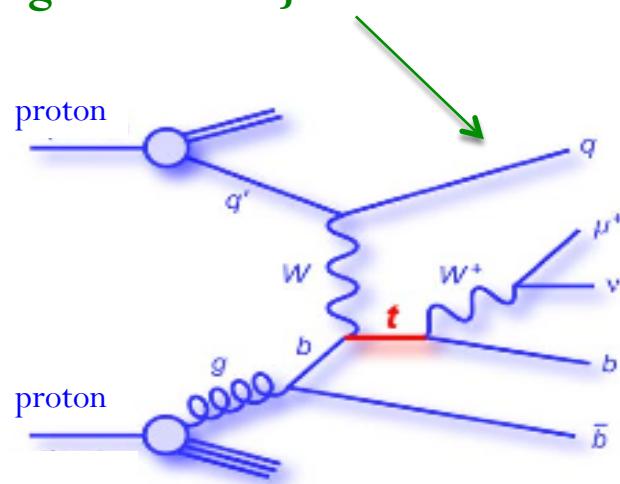
- Data sample:
 $1.17 / 1.56 \text{ fb}^{-1}$ (muon/electrons)
 - Trigger:
 - Isolated Single muon: $p_T > 17 \text{ GeV}/c$
 - single electron: $p_T > 27 \text{ GeV}/c$
 - Cross-Trigger electron+b-Jet:
 - $p_T > 25 \text{ GeV}/c$ (e) ; $p_T > 30 \text{ GeV}/c$ (jet)
 - Backgrounds
 - W+jets
 - t-tbar
 - Z+jets, VV, QCD, tW, s-channel
 - Three analyses combined with BLUE
 - $|\eta_{j'}|$ analysis (robust and little model dependence)
 - Neural Network
 - Boosted Decision Tree
- } (precise measurement,
optimized selection of
signal vs background)

t-channel @ 7 TeV: $|\eta_j|$ analysis

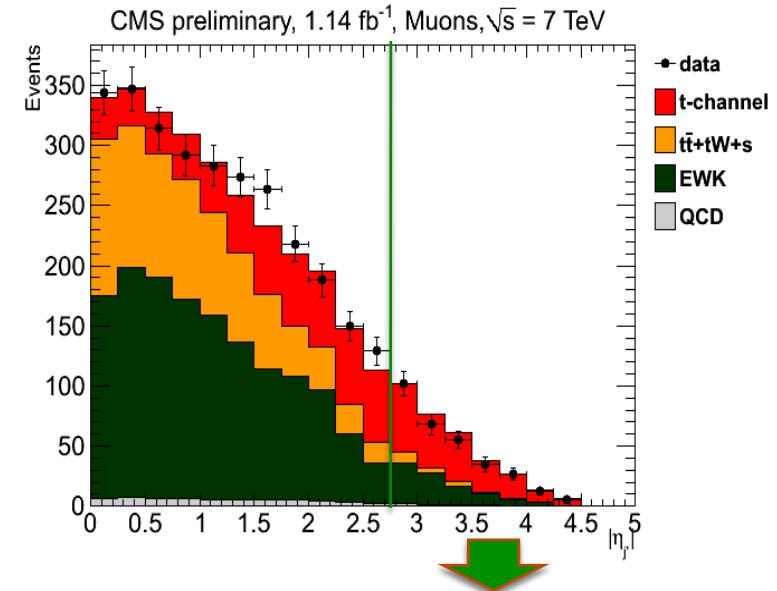


Maximum-likelihood fit to $|\eta_j|$ distribution:

η_j , angle of recoil jet



JHEP12(2012)035



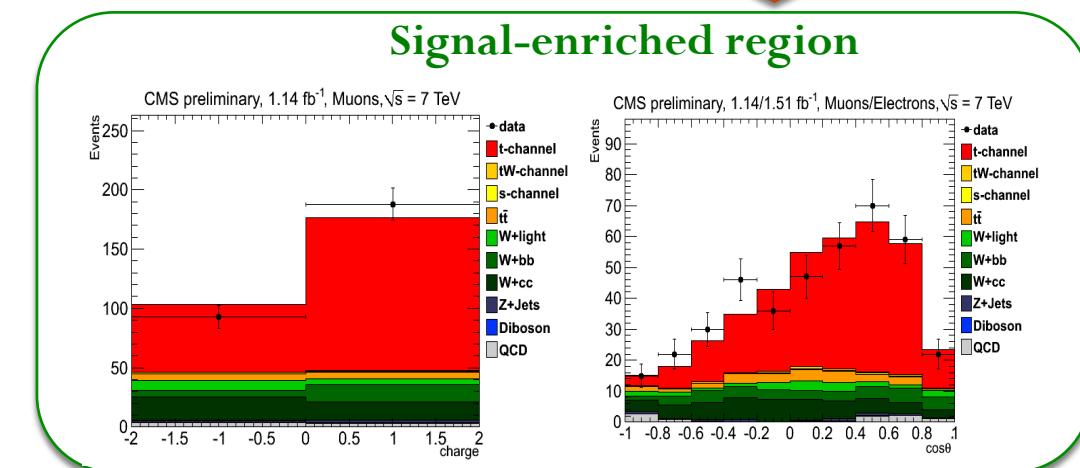
Signal:

- ✓ extracted by 2jets 1tag category

Backgrounds models from side band and extracted from fit:

- ✓ W+Jets from 2jets 0tag
- ✓ ttbar from 3jets 2tag

Signal-enriched region



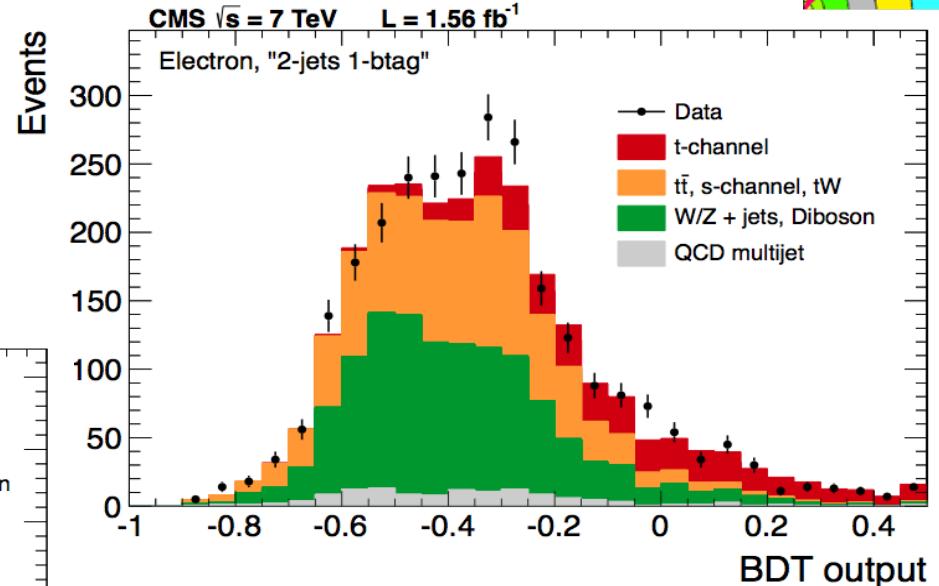
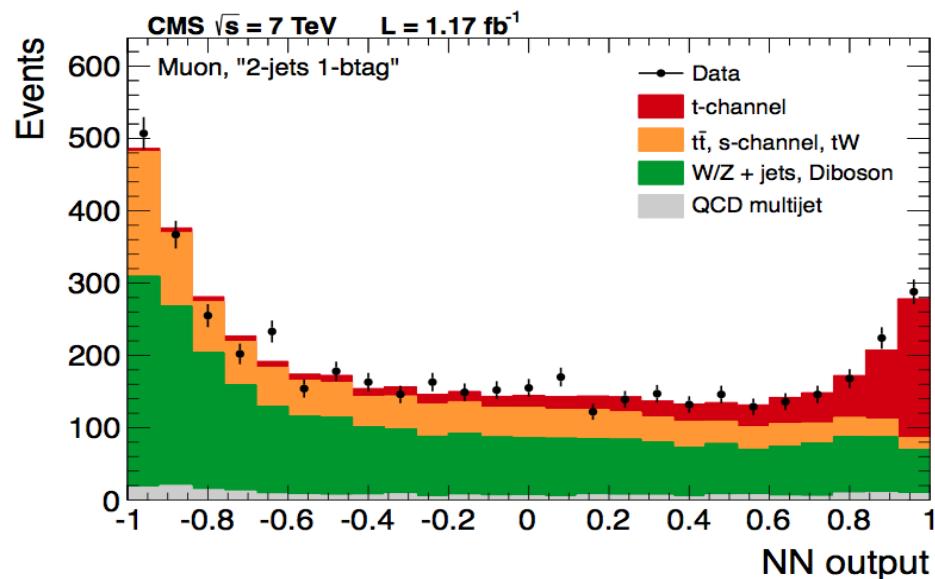
t-channel @ 7 TeV: NN and BDT



JHEP12(2012)035

Neural Network

- 6 regions:
 - 2/3/4 jets – 1/2 b-tagged jets
- 37 (38) variables in two separate NN for mu (e)



Boosted Decision Tree

- same 6 regions as NN:
- Separate training for mu and e and for 2jets 1tag and 3jets 1tag categories
- 11 variables

MVA Cross section determined with marginalized Bayesian posteriors

$$p(\mu|\text{data}) \propto \int p'(\text{data}|\mu, \vec{\theta}) \cdot \pi(\mu)\pi(\vec{\theta})d\vec{\theta}$$

Uniform prior for signal strength μ
Prior for systematic nuisance parameter

theoretical uncertainties
not marginalized

t-channel @ 7 TeV: combination



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- combination of 3 analyses with BLUE

- 60 %-75% statistical correlation between analysis
- 20 % correlation assumed for jet/ E_t^{miss} - related systematic uncertainty between MVA and $|\eta_j|$
- Others systematic assumed as 100 % correlated

$$\sigma = 67.2 \pm 3.7 \text{ (stat.)} \pm 3.0 \text{ (syst.)} \pm 3.5 \text{ (theo.)} \pm 1.5 \text{ (lum.) pb}$$

- Assuming $|V_{tb}| \gg |V_{ts}|, |V_{td}|$

$$|V_{tb}| = \sqrt{(\sigma_{\text{t-ch}} / \sigma_{\text{theo. t-ch}})}$$

$$\sigma = 67.2 \pm 3.7 \text{ (stat.)} \pm 3.0 \text{ (syst.)} \\ \pm 3.5 \text{ (theo.)} \pm 1.5 \text{ (lum.) pb}$$

$$|V_{tb}| = 1.02 \pm 0.05 \pm 0.02 \text{ (theo.)}$$

5 % precision

$$|V_{tb}| > 0.92 \text{ @95%CL for } V_{tb} \text{ in } [0,1]$$

t-channel @ 8 TeV

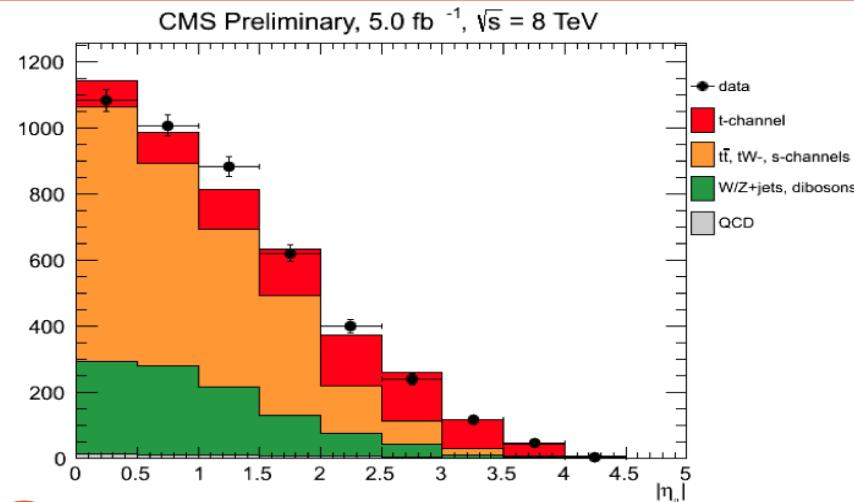


CMS PAS TOP-12-011

Main Features:

- Analysis similar to the one at 7 TeV
 - Jet $p_T > 60$ GeV/c to reduce pile-up effects
- Signal regions and control regions are defined as a function of Njets Mtags and Reconstructed top mass.
 - Signal Region: 2jets 1tag and $130 < \text{RecoTopMass} < 220$ GeV/c 2

Maximum-likelihood fit on $|\eta_j|$ distribution
in signal region



Data sample:

- 5.0 fb^{-1} (only muon)

Trigger:

- Isolated Single muon: $p_T > 26$ GeV/c
 $|\eta| < 2.1$, higher isolation cut

Background determination:

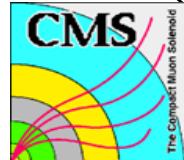
- Multijet fit in signal and sideband region separately
- ttbar shape from 3 jets, 2 b-tagged events
- W+jets shape from sideband
- other shapes taken from MC
- Z+jets use same scale as for W+jets

$$\sigma = 80.1 \pm 5.7 \text{ (stat.)} \pm 11.0 \text{ (syst.)} \pm 4.0 \text{ (lum.) pb}$$

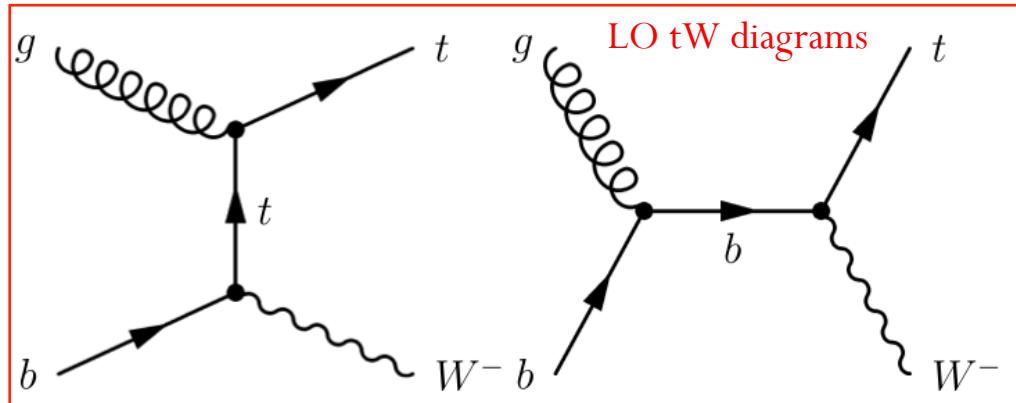
$$|V_{tb}| = 0.96 \pm 0.08 \pm 0.02 \text{ (theo.)}$$

$$|V_{tb}| > 0.81 \text{ @95%CL for } V_{tb} \text{ in } [0,1]$$

Wt-channel @ 7 TeV



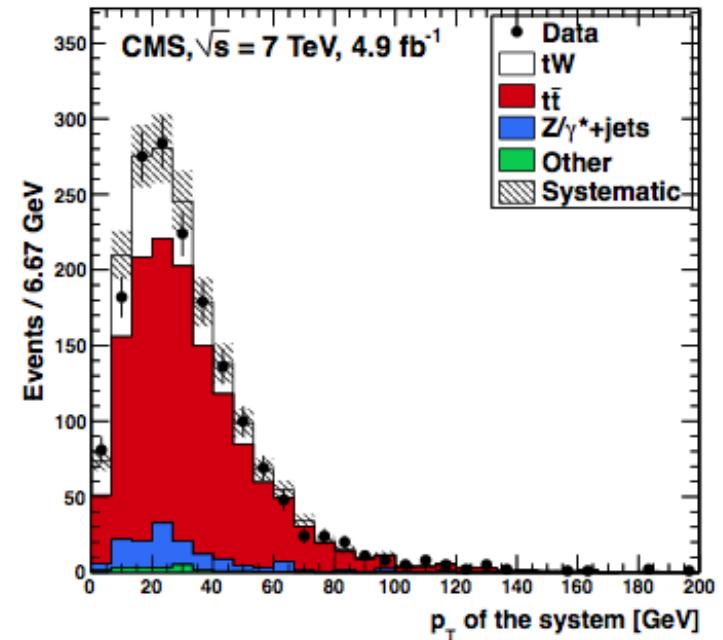
Phys. Rev. Lett. 110, 022003 (2013)



- Data sample: 4.9 fb^{-1} @ 7 TeV

- Signal generated with NLO properties and described with “diagram removal” method.
- Diagram subtraction method used as systematic effect

- selection:
 - 2 leptons with opposite charge ($p_T > 20 \text{ GeV}/c$)
 - At least one jet with $p_T > 30 \text{ GeV}/c$ and exactly one jet b-tagged in the event
 - Additional cuts on invariant mass two leptons (ee and $\mu\mu$) and E_T^{miss}
- BDT analysis with 4 variables
 - H_T , P_T of the system, P_T of most energetic jet, $\Phi(E_T^{\text{miss}} - \text{closest lepton})$



Signal and Background:

- Signal region: 1jet 1tag
- ttbar extracted from fit in regions 2jets 1tag, 2jets 2tag
- Z/γ^* E_T distributions corrected for observed data (in high pile up periods, not well modelled by MC)
- Other background negligible (<1%) and extracted by simulation

Wt-channel @ 7 TeV



Phys. Rev. Lett. 110, 022003 (2013)

Binned likelihood fit to BDT output

simultaneously in all channels (ee, e μ , $\mu\mu$)

and in signal/control regions (1jet 1tag/ 2jets 1tag, 2jets 2tags)

$$\sigma = 16^{+5}_{-4} \text{ pb}$$

4 σ level (exp. 3.6 σ)

$$V_{tb} = 1.01^{+0.16}_{-0.13} \pm 0.04 \text{ (theo.)}$$

$V_{tb} > 0.79$ @95%CL for in [0, 1]

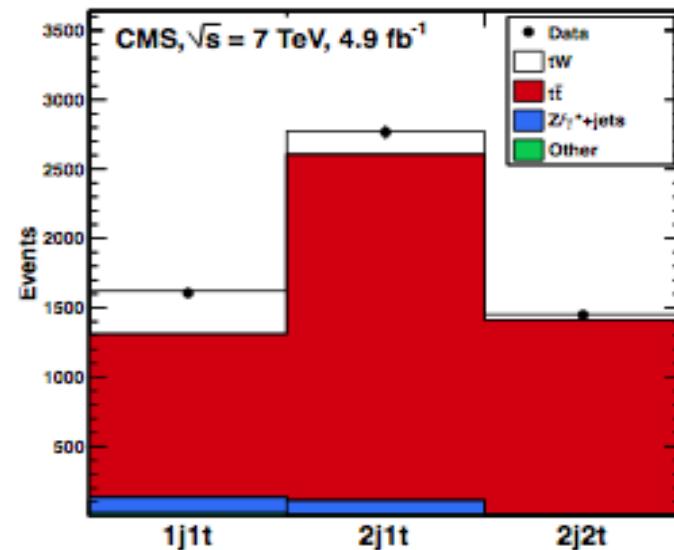
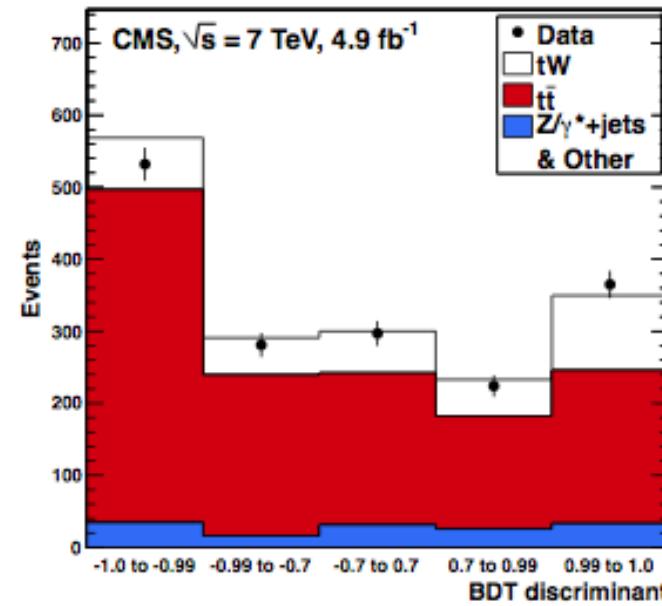
Analysis cross checked with counting method:

$$\sigma = 15 \pm 5 \text{ pb}$$

3.5 σ level (expected 3.2 σ)

Systematic:

- statistical uncertainty dominates (20%)
- Jet Energy scale main systematic (15%)

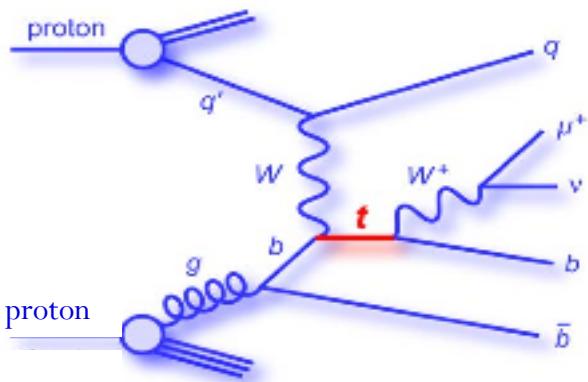


new

Single top t-channel charge ratio @ 8 TeV



CMS PAS TOP-12-038



- Asymmetry related to amount of u vs d quarks in proton
- constrain different PDF models and sensitive to NP
- t-tbar charge ratio deduced by lepton charge

SM expectations: N. Kidonakis, arXiv:1205.3453

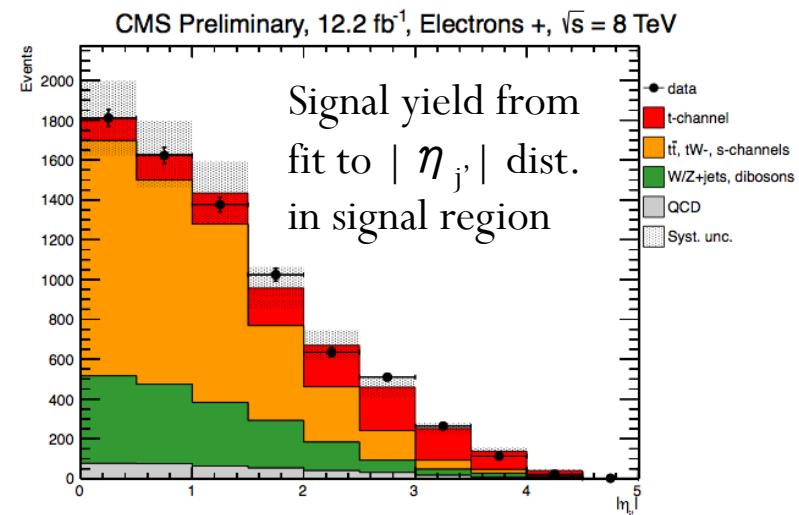
$$\sigma_{t\text{-ch.,top}}^{\text{th}} = 56.4^{+2.1}_{-0.3} \text{ (scale)}^{+1.1}_{-1.1} \text{ (PDF)} \text{ pb}$$

$$\sigma_{t\text{-ch.,anti-top}}^{\text{th}} = 30.7^{+0.7}_{-0.7} \text{ (scale)}^{+0.9}_{-1.1} \text{ (PDF)} \text{ pb}$$

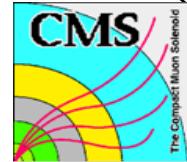
SM predictions

$$R_{t\text{-ch.}} = \sigma_{t\text{-ch.,top}} / \sigma_{t\text{-ch.,anti-top}} = 1.84$$

- Data sample: 12.2 fb^{-1} @ 8 TeV
- selection (same as t-channel):
 - Single isolated lepton (muon: $p_T > 24 \text{ GeV}/c$, electron $p_T > 27 \text{ GeV}/c$)
 - One central b-jet from top decay
 - Additional light-quark jet often in forward region
 - Additional b-jet can be present (softer pt)
 - Momentum imbalance due to neutrino
 - $m_T > 50 \text{ GeV}/c^2$ (muon)
 - $E_T > 45 \text{ GeV}/c^2$ (electron)



Single top t-channel charge ratio @ 8 TeV



CMS PAS TOP-12-038

Extended likelihood function:

$$L_{c,\ell}(N_{S_{c,\ell}}, N_{B_{c,\ell}} || |\eta|_{1_{c,\ell}}, \dots, |\eta|_{n_{c,\ell}}) = e^{-(N_{S_{c,\ell}} + N_{ewk_{c,\ell}} + N_{top_{c,\ell}} + N_{QCD_{c,\ell}})} \cdot \prod_{k_{c,\ell}=1}^{n_{c,\ell}} \left(N_{S_{c,\ell}} \cdot P_{S_{c,\ell}}(|\eta|_{k_{c,\ell}}) + N_{ewk_{c,\ell}} \cdot P_{ewk_{c,\ell}}(|\eta|_{k_{c,\ell}}) + N_{top_{c,\ell}} \cdot P_{top_{c,\ell}}(|\eta|_{k_{c,\ell}}) + N_{QCD_{c,\ell}} \cdot P_{QCD_{c,\ell}}(|\eta|_{k_{c,\ell}}) \right)$$

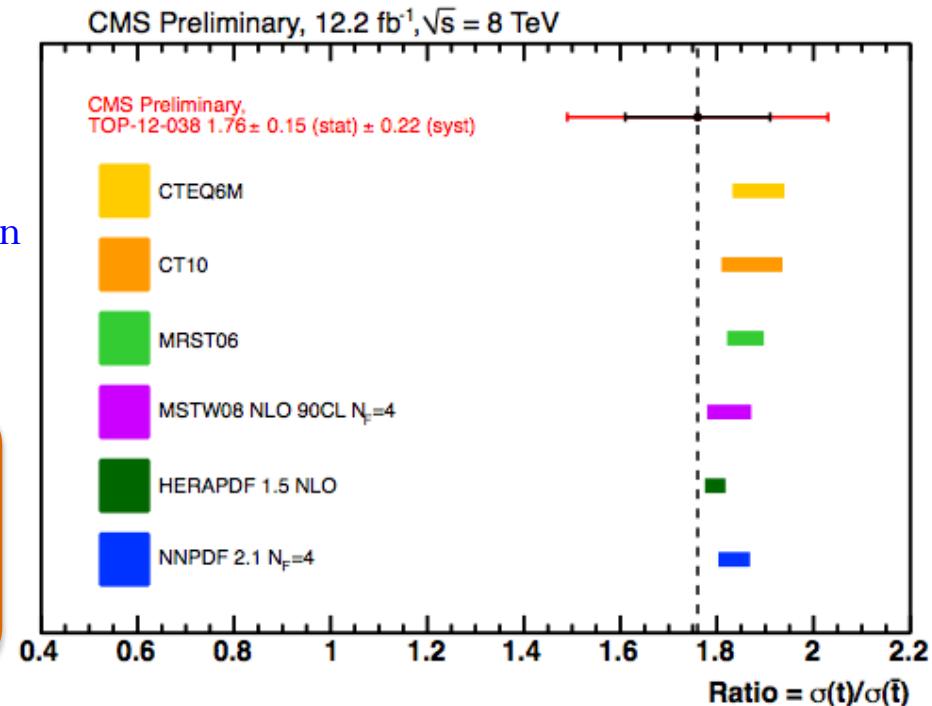
Fit performed simultaneously for leptons (l=muon/electrons) and charge (c=+/-) in the signal region:

N_S, P_S : Signal yield and binned prob. dist. function
 N_B, P_B : Background yield and binned prob. dist. function (B = ewk, top, QCD)

$$\sigma_{t\text{-ch.,top}} = 49.9 \pm 1.9(\text{stat.}) \pm 8.9(\text{syst.}) \text{ pb.}$$

$$\sigma_{t\text{-ch.,anti-top}} = 28.3 \pm 2.4(\text{stat.}) \pm 4.9(\text{syst.}) \text{ pb.}$$

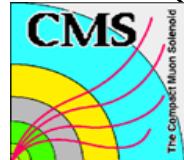
$$R_{t\text{-ch.}} = 1.76 \pm 0.15(\text{stat.}) \pm 0.22(\text{syst.})$$



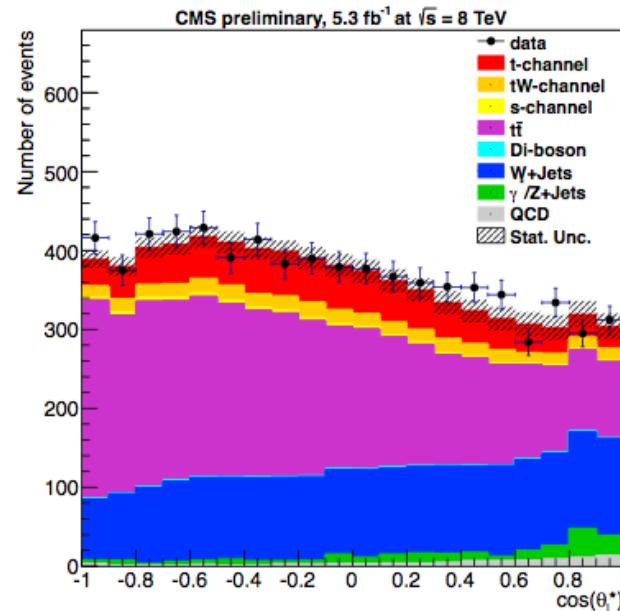
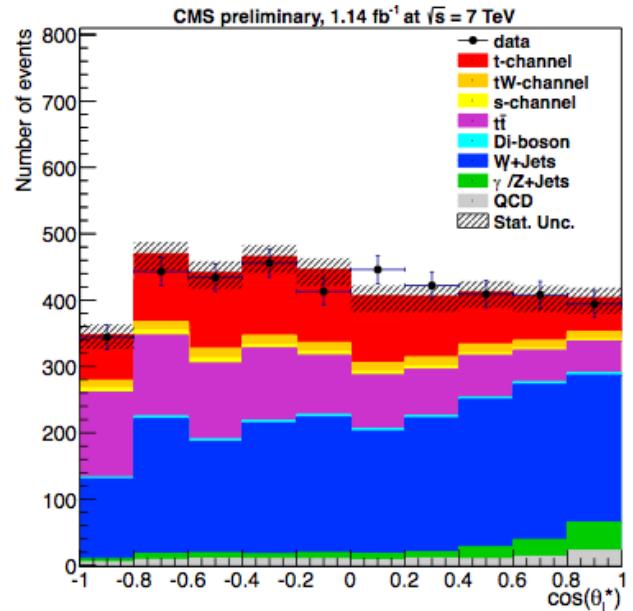
new

W-helicity in single top

CMS PAS TOP-12-020



First Measurement of W-helicity in single top events topology



$$F_L = 0.293 \pm 0.069(\text{stat.}) \pm 0.030(\text{syst.}),$$

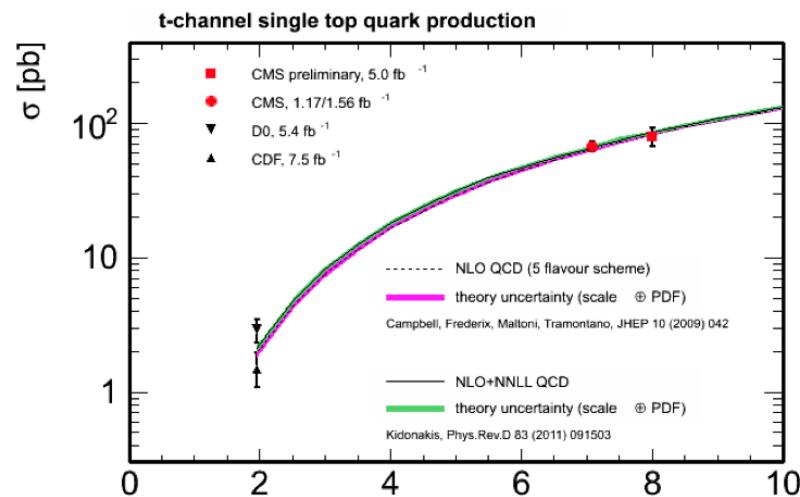
$$F_0 = 0.713 \pm 0.114(\text{stat.}) \pm 0.023(\text{syst.}),$$

$$F_R = -0.006 \pm 0.057(\text{stat.}) \pm 0.027(\text{syst.}).$$

See A. Jafari talk in this session

Conclusions

- CMS is exploring the large realm of single-top physics
- t-channel cross sections measured at 7 and 8 TeV
- tW-channel cross section, evidence at 4σ level
- constraints on $|V_{tb}|$
- t-channel charge ratio measured at 8 TeV
- First measurement of W-helicity in single top events topology
 - See A. Jafari talk in this session



Backup

t-channel @ 7 TeV

Sources of systematics

	Uncertainty source	NN	BDT	$ \eta_{ij} $
Marginalised (NN, BDT) Experimental uncert.	Statistical	-6.1/+5.5%	-4.7/+5.4%	$\pm 8.5\%$
	Limited MC data	-1.7/+2.3%	$\pm 3.1\%$	$\pm 0.9\%$
	Jet energy scale	-0.3/+1.9%	$\pm 0.6\%$	-3.9/+4.1%
	Jet energy resolution	-0.3/+0.6%	$\pm 0.1\%$	-0.7/+1.2%
	b tagging	-2.7/+3.1%	$\pm 1.6\%$	$\pm 3.1\%$
	Muon trigger + reco.	-2.2/+2.3%	$\pm 1.9\%$	-1.5/+1.7%
	Electron trigger + reco.	-0.6/+0.7%	$\pm 1.2\%$	-0.8/+0.9%
	Hadronic trigger	-1.3/+1.2%	$\pm 1.5\%$	$\pm 3.0\%$
	Pileup	-1.0/+0.9%	$\pm 0.4\%$	-0.3/+0.2%
	E_T modelling	-0.0/+0.2%	$\pm 0.2\%$	$\pm 0.5\%$
Backg. rates	W+jets	-2.0/+3.0%	-3.5/+2.5%	$\pm 5.9\%$
	light flavour (u, d, s, g)	-0.2/+0.3%	$\pm 0.4\%$	n/a
	heavy flavour (b, c)	-1.9/+2.9%	-3.5/+2.5%	n/a
	t <bar>t</bar>	-0.9/+0.8%	$\pm 1.0\%$	$\pm 3.3\%$
	QCD, muon	$\pm 0.8\%$	$\pm 1.7\%$	$\pm 0.9\%$
	QCD, electron	$\pm 0.4\%$	$\pm 0.8\%$	-0.4/+0.3%
	s-, tW ch., dibosons, Z+jets	$\pm 0.3\%$	$\pm 0.6\%$	$\pm 0.5\%$
Total marginalised uncertainty		-7.7/+7.9%	-7.7/+7.8%	n/a
Not marginalised Theor. uncert.	Luminosity		$\pm 2.2\%$	
	Scale, t <bar>t</bar>	-3.3/+1.0%	$\pm 0.9\%$	-4.0/+2.1%
	Scale, W+jets	-2.8/+0.3%	-0.0/+3.4%	n/a
	Scale, t-, s-, tW channels	-0.4/+1.0%	$\pm 0.2\%$	-2.2/+2.3%
	Matching, t <bar>t</bar>	$\pm 1.3\%$	$\pm 0.4\%$	$\pm 0.4\%$
	t-channel generator	$\pm 4.2\%$	$\pm 4.6\%$	$\pm 2.5\%$
	PDF	$\pm 1.3\%$	$\pm 1.3\%$	$\pm 2.5\%$
Total theor. uncertainty		-6.3/+4.8%	-4.9/+5.9%	-5.6/+4.9%
Syst. + theor. + luminosity uncert.		-8.1/+7.8%	-8.1/+8.4%	$\pm 10.8\%$
Total (stat. + syst. + theor. + lum.)		-10.1/+9.5%	-9.4/+10.0%	$\pm 13.8\%$

Table 2. Sources of uncertainty on the cross section measurement.

Powheg vs
CompHEP

t-channel @ 8TeV

Sources of systematics

Uncertainty source	in pb	relative
Statistical	± 5.7	$\pm 7.2\%$
W+jets and t̄t modeling	± 3.6	$\pm 4.5\%$
JES	$-6.2 / +4.7$	$-7.8 / +5.8\%$
JER	$-0.8 / +0.3$	$-1.0 / +0.4\%$
Unclustered E_T	$-0.8 / +0.7$	$-1.0 / +0.9\%$
Pileup	$-0.5 / +0.3$	$-0.6 / +0.4\%$
Muon trigger + reconstruction	$-4.1 / +4.0$	$-5.1 / +5.1\%$
Q^2	± 2.5	$\pm 3.1\%$
$t\bar{t}$, rate	$-1.5 / +1.7$	$-1.9 / +2.1\%$
QCD, rate	± 0.7	$\pm 0.9\%$
<i>t</i> -channel generator	± 4.4	$\pm 5.5\%$
Other backgrounds, rate	± 0.5	$\pm 0.6\%$
b-tagging	± 3.7	$\pm 4.6\%$
PDF	± 3.7	$\pm 4.6\%$
Simulation statistics	± 1.8	$\pm 2.2\%$
Total systematics	± 11.0	$\pm 13.7\%$
Luminosity uncertainty	± 4.0	$\pm 5.0\%$
Total	± 13.0	$\pm 16.3\%$



Powheg vs
CompHEP

Table 2: Sources of uncertainty on the signal yield.

tW-channel @7TeV

Sources of systematics

Systematic Uncertainty	$\Delta\sigma$ (pb)	$\frac{\Delta\sigma}{\sigma}$
Luminosity	0.69	0.04
Pileup modeling	0.24	0.02
Electron trigger efficiency	0.35	0.02
Muon trigger efficiency	0.38	0.02
Electron identification	0.70	0.04
Muon identification	0.45	0.03
b-tagging	0.30	0.02
Jet Energy Scale	2.42	0.15
Jet Energy Resolution	0.58	0.04
E_T^{miss} modeling	0.40	0.05
tW Q^2	0.34	0.02
$t\bar{t} Q^2$	0.29	0.02
ME/PS Matching Thresholds	1.62	0.10
tW DR/DS scheme	0.94	0.06
PDF uncertainties	0.34	0.02
$t\bar{t}$ cross section	0.96	0.06
Z/ γ^* modeling	0.67	0.04
Statistical	3.33	0.21
Total	4.95	0.31

t-channel top/anti-top ratio @ 8TeV

Sources of systematics

Uncertainty source	$\sigma_{t\text{-ch.anti}t\bar{t}\text{top}}\text{ (%)}$	$\sigma_{t\text{-ch.top}}\text{ (%)}$	$R_{t\text{-channel}}\text{ (%)}$
stat. uncertainty	± 8.6	± 3.9	± 8.8
JES,JER, and MET	± 4.9	± 4.2	± 2.6
b-tagging and mis-tag	± 4.3	± 3.7	± 0.9
backgrounds ratio	± 0.6	± 0.5	± 1.1
lepton reconstruction/trig.	± 1.9	± 1.8	± 3.6
qcd extraction	± 6.4	± 3.4	± 0.9
W+Jets, t <bar>t extraction</bar>	± 5.9	± 2.4	± 6.8
signal modeling	± 11.4	± 15.4	± 5.4
pdf uncertainty	± 5.8	± 2.8	± 7.5
simulation statistics	± 1.1	± 0.6	± 1.1
luminosity	± 4.4	± 4.4	-
total systematics	± 17.4	± 17.8	± 12.6
total relative uncertainty	± 19.4	± 18.3	± 15.3
Scale factor w.r.t. SM \pm uncertainty	0.92 ± 0.18	0.88 ± 0.16	0.96 ± 0.15

t-channel MVA analysis variables

Highest ranking variables in NN 11 variables used in BDT

- $|\eta_{j'}|$
- m_T
- Invariant mass of two leading Jets
- Total transverse energy of the event

- Pseudo-rapidity of most forward jet and highest pT
- Inv. Mass of all reco jets
- Angula sepration between two leading jets
- Sum of hadronic energy and hadronic transverse energy
- reco top quark mass
 - Using highest b-tag discriminator
 - Using the colser mass to $172 \text{ GeV}/c^2$
- Cosine of angle between reco W and leading jet
- Sum of 4-vectors of W abd leading jet
- Event sphericity