Messung des Single-Top-Wirkungsquerschnitts im t-Kanal und Bestimmung von $|V_{tb}|$ mit dem CMS-Experiment

JHEP 1212 (2012) 035

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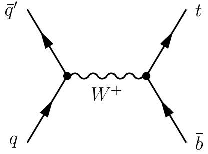
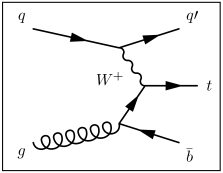
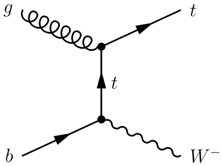
Single top production



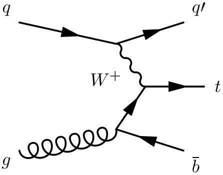


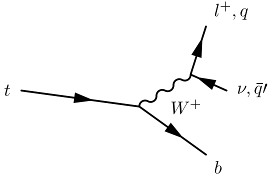


Production channel	*s*-channel	**t-channel**	*tW*
Cross section [pb]			
$p\bar{p}$ $\sqrt{s} = 1.96$ TeV	1.0	2.3	0.3
pp $\sqrt{s} = 7$ TeV	4.6 ± 0.2	$\mathbf{64.6^{+2.6}_{-1.9}}$	15.7 ± 1.2
	PRD 81, 054028	PRD 83, 091503(R)	PRD 82, 054018 (Kidonakis)

- Virtuality of the involved W boson $\rightarrow$ three different production mechanisms
- *t*-channel and *tW* cross sections largely enhanced at LHC due to gluon splitting
- *t*-channel and *tW* depend on b-quark PDF (up to 4% $\Delta\sigma$)
- Largest cross section at Tevatron and LHC: *t*-channel

Event selection





- Muon (electron+b-jet) trigger $\rightarrow$ data set 1.17/fb (1.56/fb) $\sqrt{s} = 7$ TeV
- 1 isolated muon (electron) with $p_T > 20(30)$ GeV/c and $|\eta| < 2.1$ (2.5)
- Veto electrons (muons) and loose muons (electrons) in muon (electron) decay channel
- MTW > 50 GeV/c^2 ($E_T^{miss} > 35$ GeV/c^2) to suppress QCD

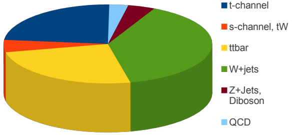
Jets

	2	3	4
0 b-tag	control region (W+light enriched)		
1 b-tag	Signal Region		$t\bar{t}$ enriched
2 b-tag			

- 2,3 or 4 jets with $p_T > 30$ GeV/c and $|\eta| < 4.5$
- 0, 1 or ≥ 2 jets with b-tag (0.1% mistag rate)

Backgrounds

- Contribution from background processes after selection:
  - Single Top: *s*-channel, *tW*
  - Top quark pair production $t\bar{t}$
  - W+jets
  - Z+jets
  - Diboson (WW, WZ, ZZ)
  - QCD multijet



- Main backgrounds: W+jets and top quark pair production $t\bar{t}$
- QCD multijet background difficult to model and MC statistics very small
  $\rightarrow$ data driven estimation with fit to MTW (MET) in orthogonal data set

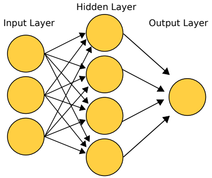
Separation:

- Pseudorapidity of light quark mostly in forward region
- Other variables alone: not much separation power
- $\rightarrow$ Use a multivariate technique: neural networks

Multivariate analysis with neural networks

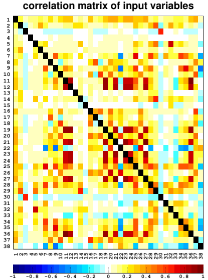
NeuroBayes:

- Robust preprocessing of input variables (Decorrelation, transformation to Gaussian)
- Spline-fit to variables to be robust against statistical fluctuations or noise
- Method has been checked with bootstrapping

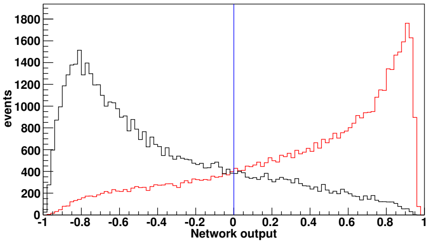


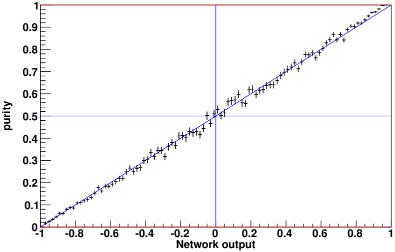
Input variables:

- Only use well modeled variables (good KS test values in control region)
- Network rejects variables with low significance
- 37 variables in muon channel
  38 variables in electron channel
- Most important variables: light quark η, H_T, $M_{jet1,jet2}$



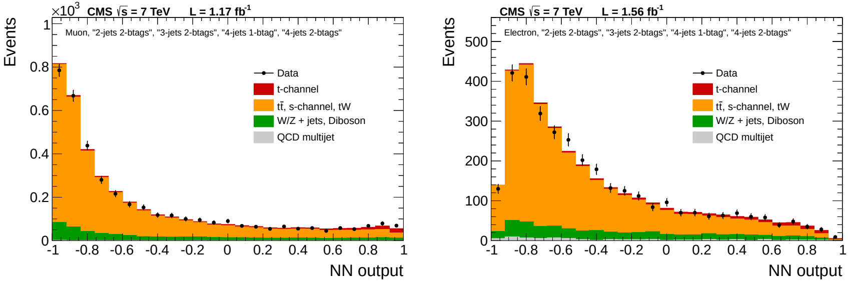
Neural network - training





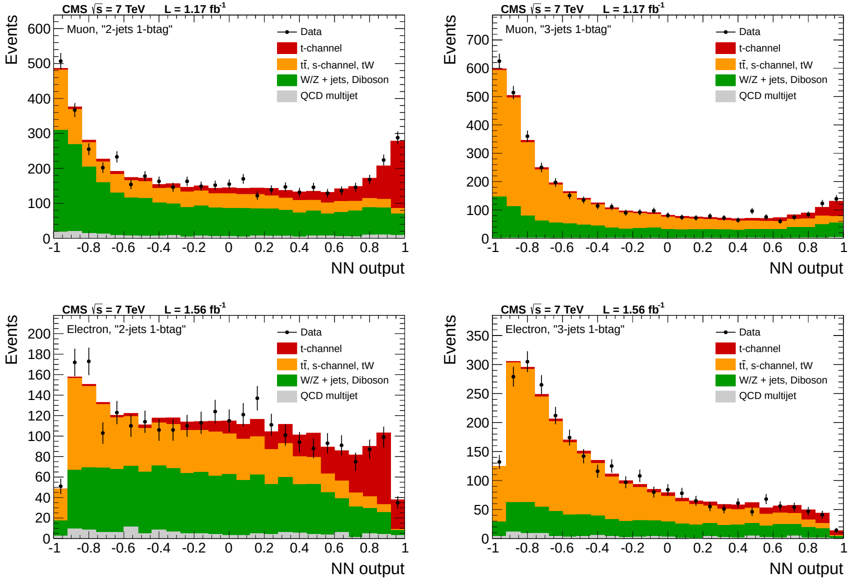
- Signal/background ratio 50:50 (*t*-channel vs $t\bar{t}$, *W*+jets, *Z*+jets)
- Network can separate **signal** and **background**
- Purity increases with discriminator output

Neural network - discriminator in background region



- Discriminator output well modeled in $t\bar{t}$ enriched background region
- We use this region for the estimation of top quark pair production and to constrain systematic effects

Neural network - discriminator in signal region



Statistical inference

- Bayesian method

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

- Impact of systematic effects marginalized as nuisance parameters (JER, JES, b-tagging, ...)
- Influence of theoretical uncertainties studied separately, not marginalized (Renormalization/factorization (Q^2 scale), matching, PDF, different signal generator)
- Integration via Markov Chain Monte Carlo (MCMC)
- Statistical framework: `http://www.theta-framework.org`
- Result:

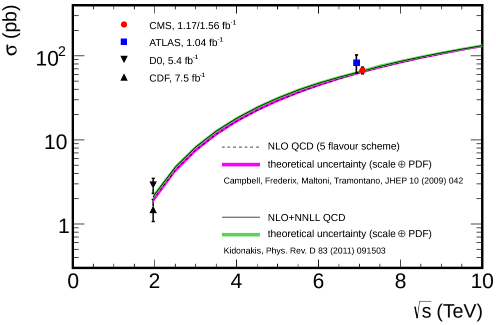
$$\sigma_{t\text{-ch.}} = 68.1 \pm 4.1\ (\text{stat.}) \pm 3.4\ (\text{syst.})^{+3.3}_{-4.3}\ (\text{theor.}) \pm 1.5\ (\text{lum.})\ \text{pb}$$

Combination - Result

- This measurement is combined with two other approaches: a robust template fit to light quark η and MVA method with BDT
- Combining all three analyses with BLUE yields a cross section of

$$\sigma_{\text{t-ch.}} = \boxed{67.2 \pm 6.1 \text{ pb}} = 67.2 \pm 3.7 \text{ (stat.)} \pm 3.0 \text{ (syst.)} \pm 3.5 \text{ (theor.)} \pm 1.5 \text{ (lum.) pb}$$

- with a relative uncertainty of 9.1%



- Published in **JHEP 1212 (2012) 035**, CMS-TOP-011-021 (arXiv:1209.4533)

Combination - Estimation of $|V_{tb}|$

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- Under the assumption that $|V_{tb}|^2 \gg |V_{td}|^2 + |V_{ts}|^2$ and $|V_{tb}| = 1$ for $\sigma^{\text{th}}_{t\text{-ch.}}$
- One can extract $|V_{tb}|$ from the cross section measurement

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

$$|f_{L_V} V_{\text{tb}}| = \sqrt{\frac{\sigma_{t\text{-ch.}}}{\sigma^{\text{th}}_{t\text{-ch.}}}} = 1.020 \pm 0.046\ (\text{exp.}) \pm 0.017\ (\text{theor.})$$

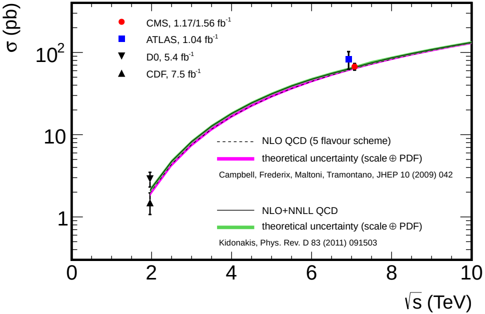
- with a possible anomalous form factor f_L from BSM models
- Constraining $|V_{tb}|$ to the interval $[0, 1]$ and setting $f_L = 1$ yields: (Feldman Cousins)

$$0.92 < |V_{tb}| \leq 1 @ 95\%\ \text{CL}$$

- Tightest constraint from direct measurement!

Conclusion

- Measured single top t-channel cross section and $|V_{tb}|$ with neural network analysis in multiple channels at $\sqrt{s} = 7$ TeV
- Combination yields cross section with relative uncertainty $< 10\%$
- Most precise single top *t*-channel cross section measurement
- $|V_{tb}| \approx 1$ and $0.92 < |V_{tb}| \leq 1$ @ 95% CL
- Results published in JHEP 1212 (2012) 035



Conclusion and outlook

Conclusion:

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- Combination yields cross section with relative uncertainty $< 10\%$
- Most precise single top t-channel cross section measurement
- $|V_{tb}| \approx 1$ and $0.92 < |V_{tb}| \leq 1$ @ 95% CL
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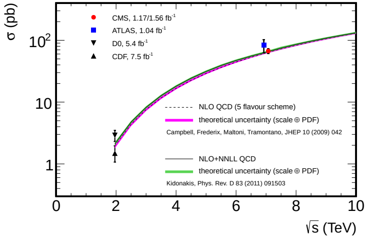
Outlook:

- Last year: 20/fb of data at $\sqrt{s} = 8$ TeV
- Now detailed studies of theory possible:
  - Precise measurement at $\sqrt{s} = 8$ TeV
  - Charge asymmetry measurement
  - Differential measurement in top p_T and η
  - Polarization of top quarks
  - ...



Backup

Single top - history and motivation

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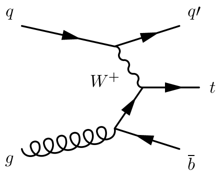
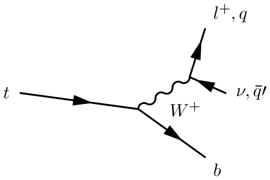
- Single top quark production first discovered in 2009 at Tevatron by CDF and DØ
- Discovery in s+t-channel after long and difficult search
- Rediscovery of t-channel in 2011 at LHC with first data
- Can now be studied in detail at LHC

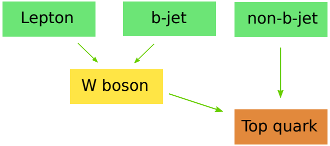


Interesting properties:

- Allows direct measurement of CKM matrix element $|V_{tb}|$
- Sensitive to b quark PDF
- *Wtb* coupling enables tests of V–A structure, anomalous couplings
- Allows study of top quark polarization
- Background for Higgs and search for new physics/SUSY (4th generation, H^+, $W^{'}$)

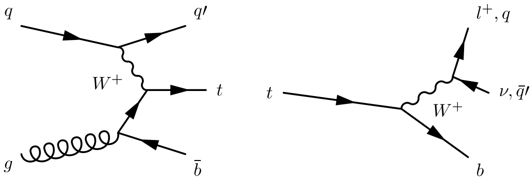
Top quark reconstruction



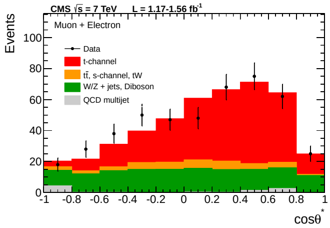


- Reconstructed from detector: jets, leptons, E_T^{miss}
- Top quark candidate reconstructed from W boson and *b*-tagged jet
- W boson from lepton and E_T^{miss} : $p_{z,\nu}$ from E_T^{miss} by constraint on W boson mass
  - Two real solutions: Choose the one with smallest $|p_{z,\nu}|$
  - Imaginary solution: Minimal variation of E_T^{miss} so that $M_T^W = M_W$
- Assign *b*-tagged jet to top quark decay
  - Assignment of top quark correct in approx. 88% of cases (MC studies)

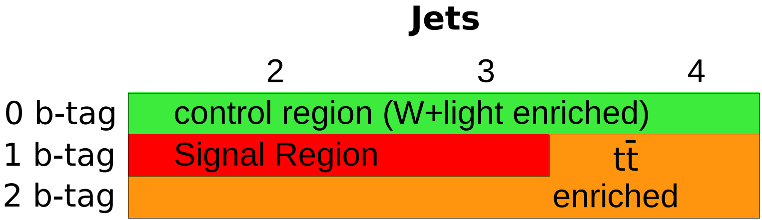
Top quark decay



- Top quark decays immediately due to high mass / large width
- Top quark decays into *W* boson and *b* quark (SM: BR ≈ 100%)
- W boson from top-quark decay further decays into charged lepton and neutrino (BR ≈ 32%), here only muon and electron channel
- Spin information passed to decay products



Analysis regions



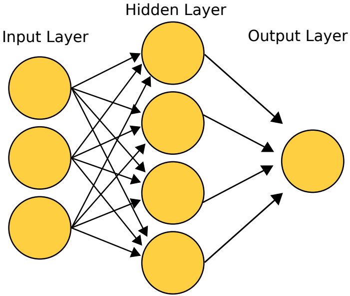
- Events without *b*-tag:
  (W+light enriched) control region of input variables
- Events with $\geq$ 2 b-tags:
  Estimation of top quark pair production and constraint of systematic effects

Neural network

- Artificial neural networks (NN) modeled after biological neural networks
- Multiple nodes with nonlinear activation function in three or more layers, each node connected to every node in the next layer with specific weight
- The network learns by minimizing an error function and changing the weights (Supervised learning, backpropagation)

NeuroBayes:

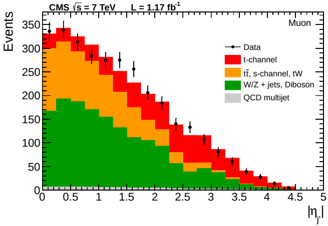
- 3-layer feedforward network
- Robust preprocessing of input variables (Decorrelation, transformation to Gaussian)
- Spline-fit to variables to be robust against statistical fluctuations or noise



Combination - Details

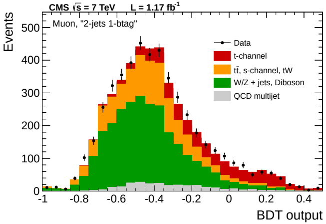
This measurement is combined with two other measurements:

- Light quark η analysis (Napoli)
  - Template fit to light quark η
  - W+jets background data driven
  - One analysis bin (2 jets 1 tag)



- BDT analysis (Aachen)
  - MVA analysis (BDT)
  - Bayesian method
  - Multiple analysis bins

  } same as NN (Bayesian method, Multiple analysis bins)



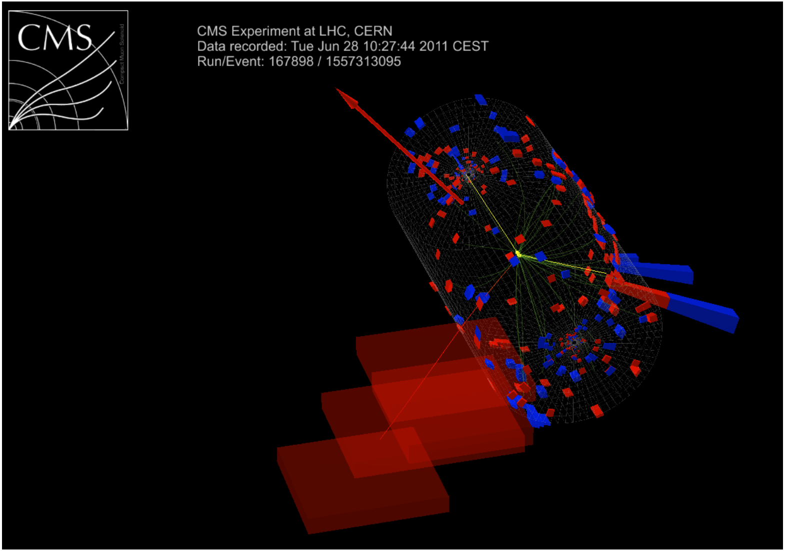
- All three analyses employ the same selection
- Correlation is estimated by dicing toys

Systematic effects

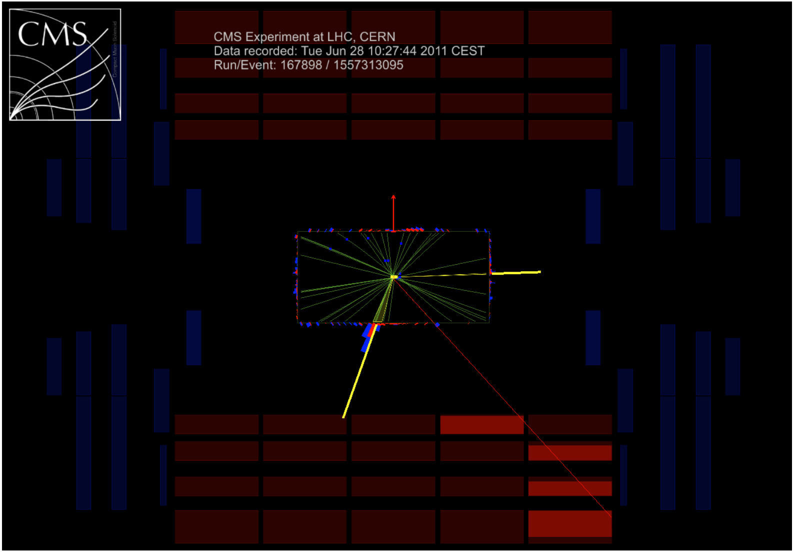
Table: Sources of uncertainty on the cross section measurement.

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

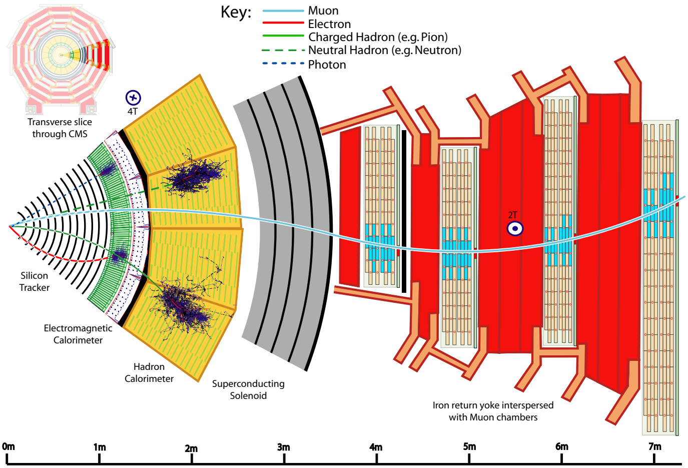
Event Display - 3D view



Event Display - $\rho - z$ plane



CMS detector



- Single top analyses need information from all detector subsystems to reconstruct (forward) jets, leptons, and missing transverse energy (E_T^{miss})