BROWN

Single Top Production at CMS

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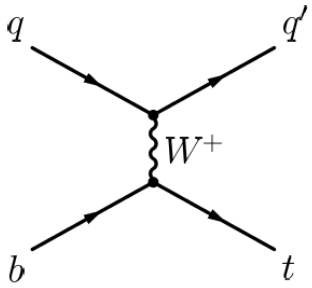
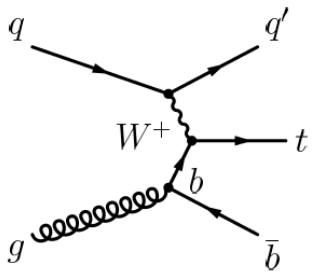
Introduction

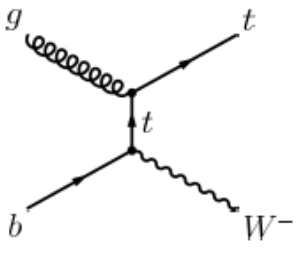
- Single top production established at the Tevatron
- Three different production mechanisms in SM:



t channel

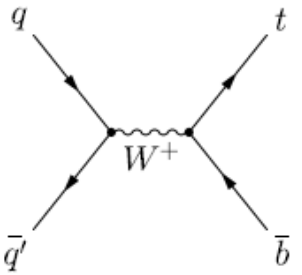
σ_{SM} = 62 pb





tW channel

σ_{SM} = 11 pb



s channel

σ_{SM} = 4 pb

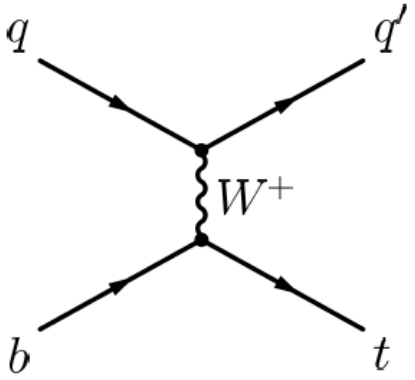
- Single top production in the *t* channel
  - Largest cross section, characteristic final state topology
  - Small signal with large backgrounds
  - Detailed understanding of the background and the detector
- Sensitive to contributions from non-SM physics
- Measurement of $|V_{tb}|$

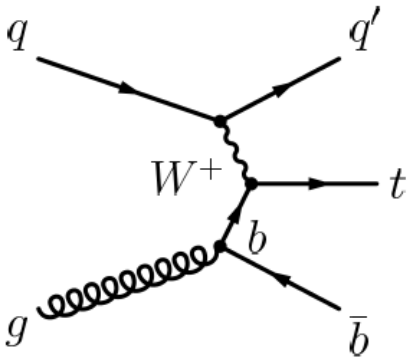
Introduction

- First measurements of single top production at CMS
  - Use full 2010 dataset (35.9 ± 1.4 pb^{-1})
  - CMS-PAS-TOP-10-008, arxiv:1106.3052, to be published in Phys.Rev.Lett.
- Require leptonic decay of W: $t \rightarrow bl\nu$ (e or μ)
- 2 measurement methods used
- Angular analysis (2D)
  - 2D fit to angular properties of the signal
  - Data driven background estimate
  - Minimum model dependence
- Multivariate analysis (BDT)
  - Probe the overall compatibility of candidates with SM expectations
  - Best use of information from event trough use of Boosted Decision Tree
  - Maximum sensitivity
- Results combined using BLUE method

Topology

- Expected topology
  - W from decay of t quark
    - Leptonic decay W → lν (e or μ)
    - lν-mass: peak at the W mass (jacobian peak)
  - Central b jet from top
    - lνb peak at the top mass
  - Light jet from recoil in forward direction
  - Very soft additional b jet
- Main backgrounds:
  - QCD multijet events
  - W/Z boson + jets
  - $t\bar{t}$ quark pairs





Event Selection

- Inclusive single lepton triggers
  - Muon with p_T > 9 - 15 GeV or electron with E_T > 10 - 22 GeV
- Leading isolated, prompt lepton (e or μ):
  - electrons: p_T > 30 GeV and $|\eta|$< 2.5
  - muons: p_T > 20 GeV and $|\eta|$< 2.4
  - Veto events with 2nd lepton
- Exactly 2 jets with p_T > 30 GeV, $|\eta|$< 5
  - Anti-k_T (R=0.5), particle flow based algorithm
  - b-tagging:
    - Exactly one b-tagged jet (high purity tagger)
    - 2D analysis: veto event with additional b-tagged jet (high eff. tagger)
  - BDT analysis: remove back-to-back jets $\Delta\varphi$ (j_1,j_2) > 3 (poorly reproduced in MC)
- Select events with leptons compatible with W decay:
  - Transverse mass: M_T > 40 (50) GeV/c^2, for muon (electrons)
  - MET assumed to originate from ν

$$M_T = \sqrt{(p_{T,l} + p_{T,\nu})^2 - (p_{x,l} + p_{x,\nu})^2 - (p_{y,l} + p_{y,\nu})^2}$$

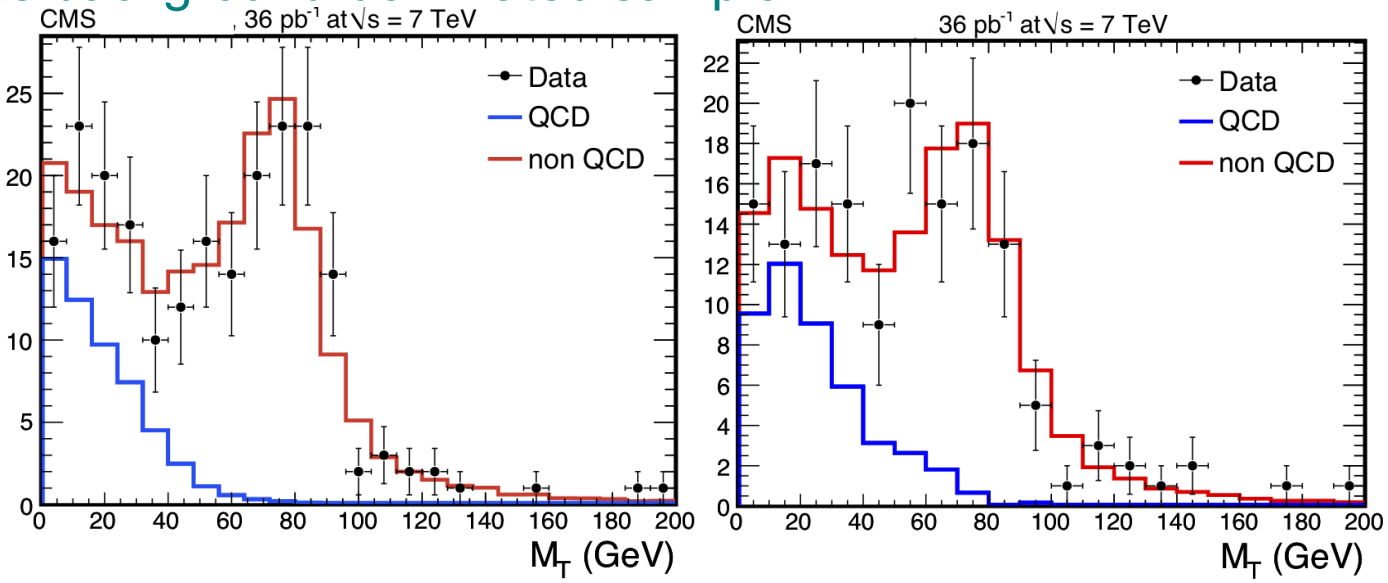
Background estimation: QCD background

- Data-driven estimate of QCD background needed:
  - kinematic phase space populated by tail of the QCD distribution
- Normalisation: profile likelihood fit to M_T distribution

$$F(M_T) = a \cdot S(M_T) + b \cdot B(M_T)$$

  - $S(M_T)$: template for signal-like contributions, from MC
  - $B(M_T)$: template for QCD-like events, from a control sample in data
    - no b-tagging requirements, invert isolation cut
    - rejects most of the signal-like events (single top, W + X, $t\bar{t}$, etc)
    - high-statistics background-dominated sample

MT distributions
for BDT selection
- left: muons
- right: electrion



Background estimation: QCD background

- Prediction for QCD background in data:
  - 2D

$$N_{qcd}^{2D} = 0.62 \pm 0.12(stat.) \pm 0.08(shape) \pm 0.15(stability) \quad \text{muons}$$
$$N_{acd}^{2D} = 2.6 \pm 0.6(stat.) \pm 3.1(shape) \pm 1.2(stability) \quad \text{electrons}$$

  - BDT

$$N_{qcd}^{BDT} = 4.92 \pm 0.99(stat.) \pm 0.05(shape) \pm 0.81(stability) \quad \text{muons}$$
$$N_{qcd}^{BDT} = 5.27 \pm 1.24(stat.) \pm 0.79(shape) \pm 3.23(stability) \quad \text{electrons}$$

  - Central value taken as prediction
  - Conservative uncertainties, ± 50% to ± 100% of value

Background estimation

- W + light jets:
  - 2D analysis: similar data driven method
    - Selection: one isolated lepton + exactly 2 taggable jets, but fail b-tag
    - Extract scale factor and distribution of variables used in fit
    - Same scale factor used for Z+jets
  - BDT analysis: W+light jets treated as nuisance parameter in the fit

- Other background contributions
  - 2D analysis:
    - Single top, s & tW channels, VV: from MC
    - VQQ , Wc rescaled to LO + factors, derived in tt cross section analysis
  - BDT analysis: normalization of backgrounds treated as nuisance parameter in the fit, Gaussian constraints corresponding to systematic uncertainties

Event yields

Process	2D, μ channel	2D, e channel	BDT, μ channel	BDT, e channel
single top, t channel	17.6 ± 0.7	11.2 ± 0.4	17.6 ± 0.7	10.7 ± 0.5
single top, s channel	0.9 ± 0.3	0.6 ± 0.2	1.4 ± 0.5	1.0 ± 0.3
single top, tW	3.1 ± 0.9	2.4 ± 0.7	3.8 ± 1.1	< 0.1
WW	0.29 ± 0.09	0.23 ± 0.07	0.32 ± 0.10	0.23 ± 0.07
WZ	0.24 ± 0.07	0.17 ± 0.05	0.33 ± 0.10	1.5 ± 0.4
ZZ	0.018 ± 0.005	0.011 ± 0.003	0.020 ± 0.006	< 0.1
$W+$ light partons	18.2 ± 5.5	11.6 ± 2.3	8.4 ± 4.2	7.0 ± 3.5
$Z + X$	1.7 ± 0.5	1.6 ± 0.3	0.7 ± 0.2	0.05 ± 0.03
QCD	0.6 ± 0.3	$2.6^{+3.4}_{-2.6}$	4.9 ± 2.5	5.3 ± 5.3
$VQ\bar{Q}$	20.4 ± 10.2	14.1 ± 7.1	17.6 ± 8.8	11.7 ± 5.8
Wc	$12.9^{+12.9}_{-6.5}$	$9.4^{+9.4}_{-4.7}$	$9.2^{+9.2}_{-4.6}$	$5.9^{+5.9}_{-2.9}$
$t\bar{t}$	20.3 ± 3.6	15.6 ± 2.8	34.9 ± 4.9	22.9 ± 3.2
Total background	78.6 ± 15.2	58.4 ± 11.0	82.4 ± 13.1	55.9 ± 10.2
Signal + background	96.2 ± 15.3	69.6 ± 11.0	100.0 ± 13.2	66.6 ± 10.2
Data	112	72	139	82

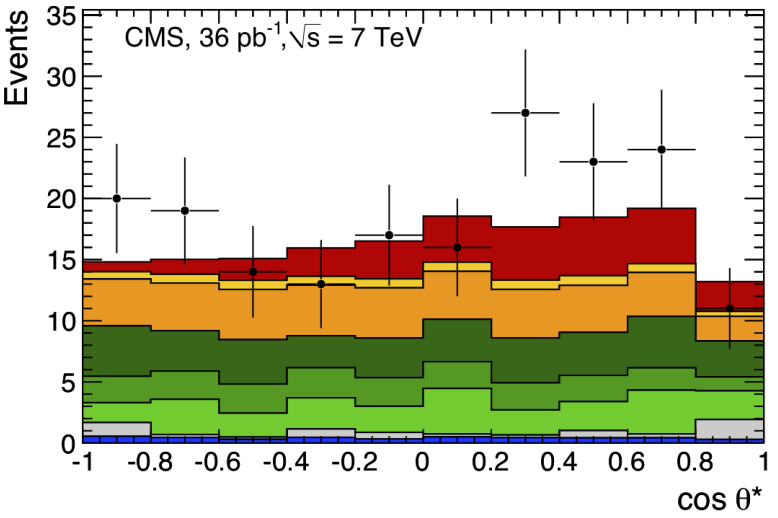
Single top t-channel: $\sigma^{th} = 62.3^{+2.3}_{-2.4}\mathrm{pb}$ NLO, 5-flavour scheme, JHEP (2009) 042

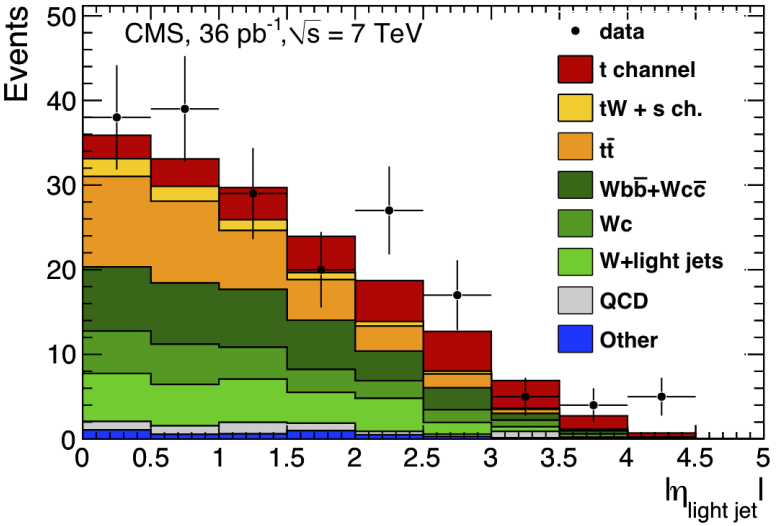
The 2D analysis

- Unbinned likelihood fit to 2D cos Θ_{lj} – η_{lj} distribution
- Θ_{lj} : angle between lepton and the spin axis (taken as light jet)
  - V – A structure of weak interaction: ~100% left-handed polarization of the top quark with respect to the spin axis
  - Angular correlations of its decay products:

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta^*_{lj}} = \frac{1}{2}(1 + A\cos\theta^*_{lj})$$

- η_{lj} : pseudorapidity distribution of untagged jet
- Separate fit in e & μ channels
- Templates from MC, except QCD, W + light jets



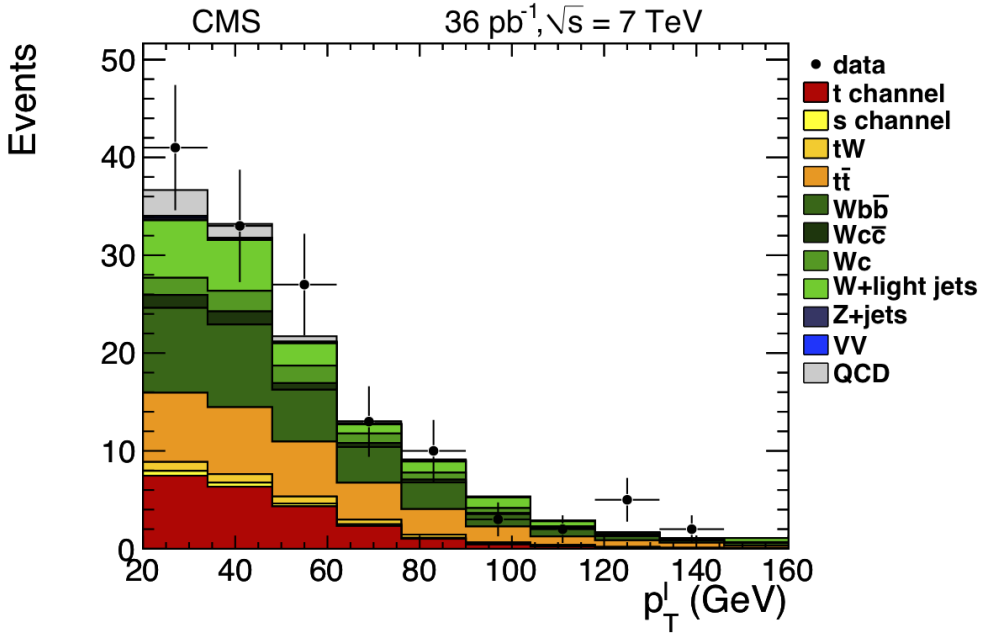


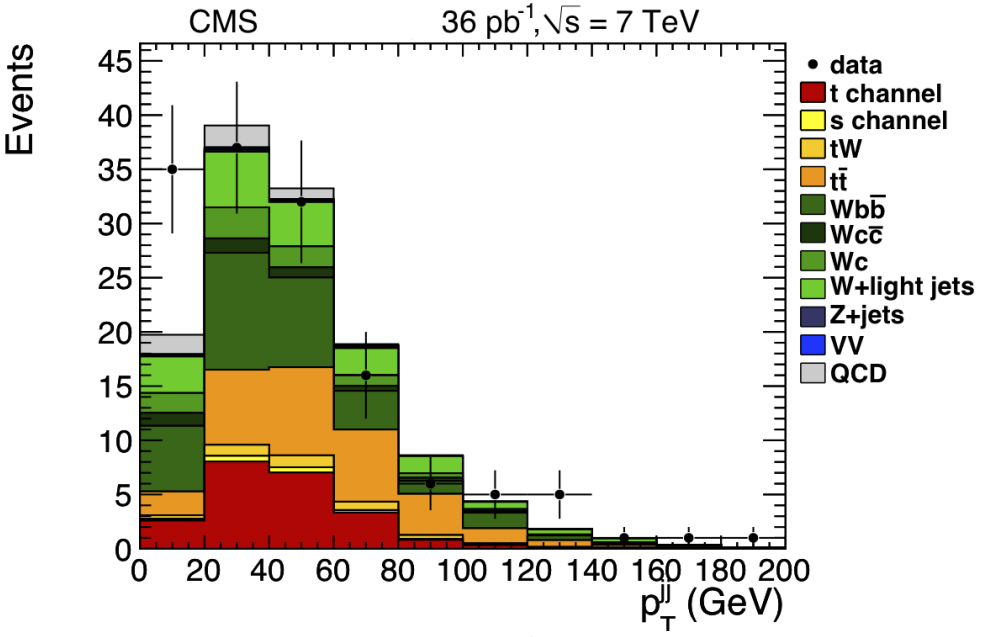
Distributions in data for mu+e channels together

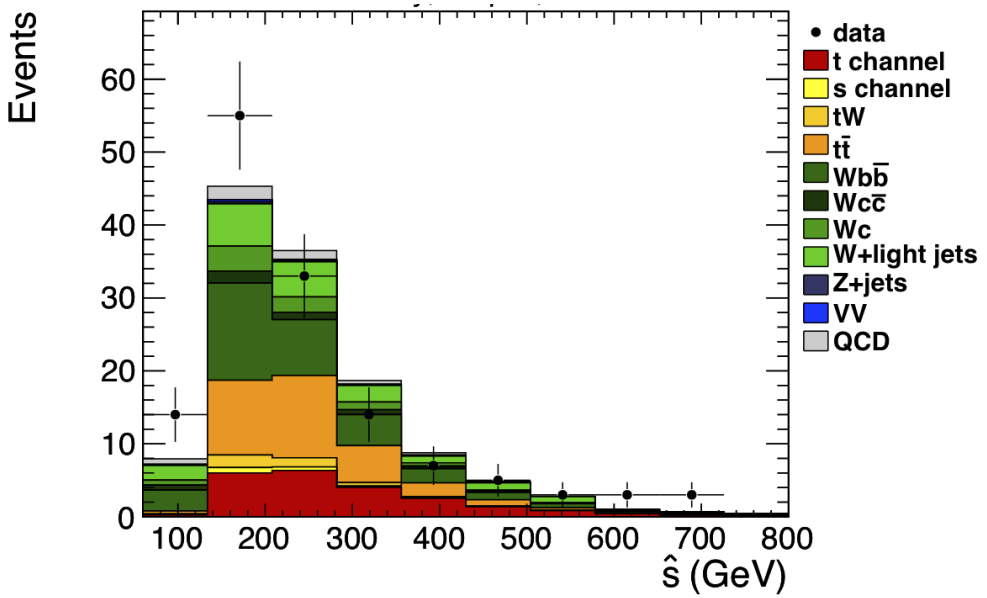
The multivariate analysis (BDT)

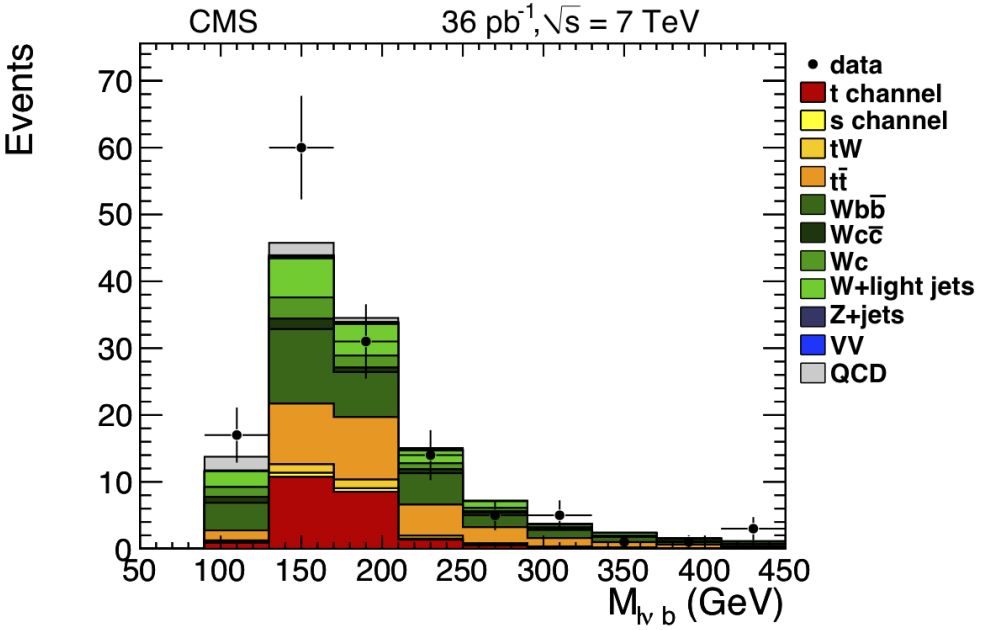
- Exploit the compatibility of the data with the SM predictions
- Boosted Decision Tree (BDT):
  - Combines set of observables into single classifier observable *bdt*
  - Use 1000 decision trees and ADA boosting algorithm (in TMVA)
- 37 observables, from 5 categories:
  - Kinematics and properties of final-state objects
  - Correlations between final-state objects
  - Properties of reconstructed W, t, t+q
  - Angular distributions between objects
  - Event related observables
- Validity of description of the input variables in MC checked using a Kolmogorov-Smirnov test in the orthogonal W-enriched control sample

BDT inputs



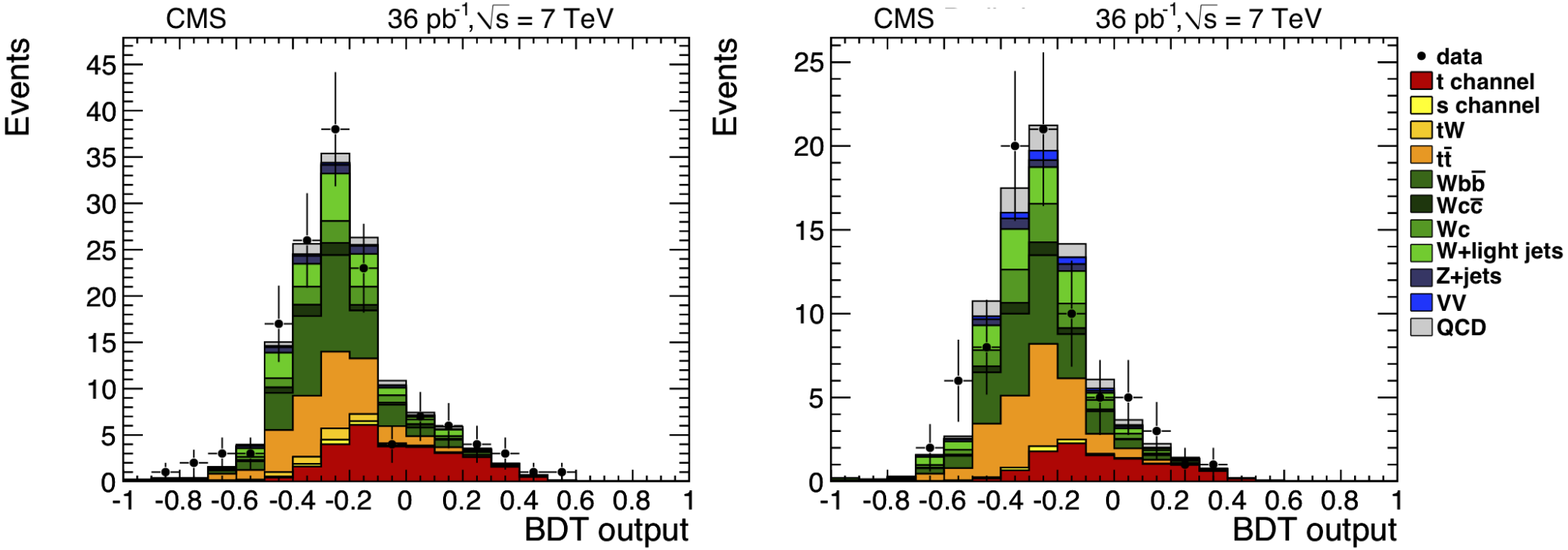






Distribution of a few of the main observables (here for μ channel only)

The *bdt* discriminant



bdt discriminant for the muon and electron channels

- Predicted backgrounds are scaled to the medians of their posteriors from the fit
- *bdt* classifier validated in simulation and data

- Cross section measurement: binned likelihood fit to *bdt* with a Bayesian approach

Systematic uncertainties

uncertainty	correlation	impact on 2D −	2D +	BDT −	BDT +
statistical only	60	52		39	
shared shape/rate uncertainties:					
ISR/FSR for $t\bar{t}$	100	−1.0	+1.5	< 0.2	< 0.2
Q^2 for $t\bar{t}$	100	+3.5	−3.5	+0.3	−0.4
Q^2 for V+jets	100	+5.7	−12.0	+2.6	−4.5
Jet energy scale	100	−8.8	+3.6	−5.1	+1.2
b tagging efficiency	100	−19.6	+19.8	−15.2	+14.6
MET (uncl. energy)	100	−5.7	+3.7	−3.9	−0.5
shared rate-only uncertainties:					
$t\bar{t}$ (±14%)	100	+2.0	−1.9	+0.5	−0.6
single top s (±30%)	100	−0.4	+0.5	−0.4	+0.4
single top tW (±30%)	100	+1.1	−1.0	< 0.2	< 0.2
$Wb\bar{b}$, $Wc\bar{c}$ (±50%)	100	−3.0	+2.9	+1.7	−1.9
Wc $(^{+100\%}_{-50\%})$	100	−3.0	+6.1	−2.4	+4.4
Z+jets (±30%)	100	−0.6	+0.7	+0.4	−0.2
electron QCD (BDT: ±100%, 2D: $^{+130\%}_{-100\%}$)	50	+2.9	−3.7	−1.7	+1.7
muon QCD (BDT: ±50%, 2D: ±50%)	50	< 0.2	< 0.2	−2.1	+2.1
signal model	100	−5.0	+5.0	−4.0	+4.0
BDT-only uncertainties:					
electron efficiency (±5%)	0	—	—	−1.4	+1.4
muon efficiency (±5%)	0	—	—	−3.6	+3.5
V+jets (±50%)	0	—	—	−1.5	< 0.2
2D-only uncertainties:					
muon W+light (±30%)	0	−1.4	+1.4	—	—
electron W+light (±20%)	0	−0.6	+0.7	—	—
W+light model uncertainties	0	−5.4	+5.4	—	—

Relative impact of the uncertainties on the combined cross section measurement (e+μ), in % of SM cross section, estimated with pseudo-data.

Systematic uncertainties

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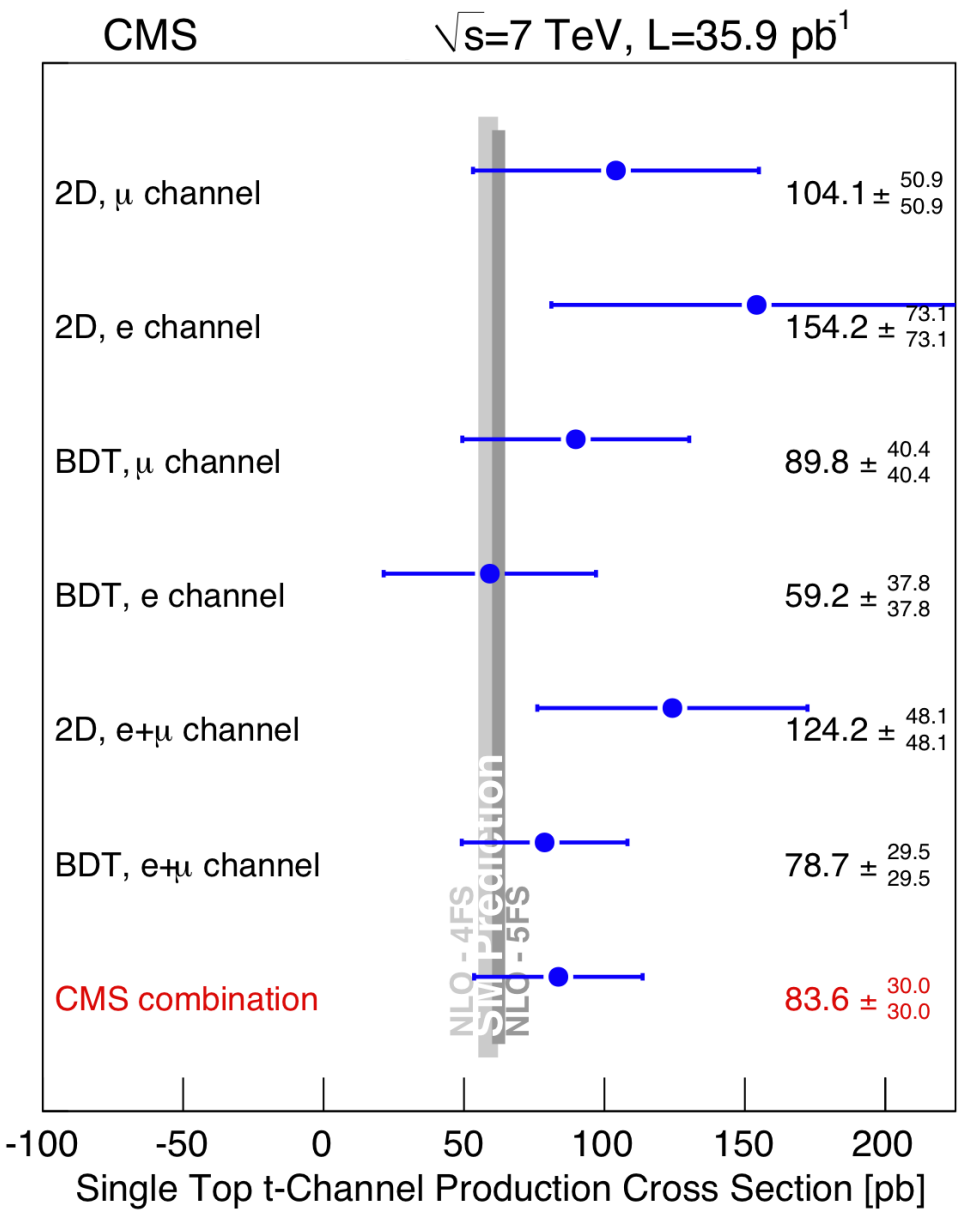
W+light model uncertainties	0	−5.4	+5.4	—	—

Largest contribution: b-tagging uncertainty

- 2011: uncertainty reduced, latest performance measurement done on 0.5 fb^{-1}

Relative impact of the uncertainties on the combined cross section measurement (e+μ), in % of SM cross section, estimated with pseudo-data.

Result



- Measurements combined using the Best Linear Unbiased Estimator (BLUE)
  - Statistical correlation factor is determined from pseudo-experiments
  - Correlation factor: 0.6

$\sigma = 83.6 \pm 29.8$ (stat+syst) ± 3.3 (lumi) pb

- Expected and observed significances, (in number of Gaussian std. dev.)

Analysis, channel	expected	observed
2D, μ-channel	$1.7^{+1.1}_{-1.0}$	2.5
2D, e-channel	$1.3^{+1.0}_{-1.1}$	3.1
2D, combined	$2.1^{+1.0}_{-1.1}$	3.7
BDT, μ-channel	$2.4^{+0.9}_{-1.0}$	3.1
BDT, e-channel	2.0 ± 1.0	1.9
BDT, combined	$2.9^{+1.0}_{-0.9}$	3.5

Limits on $|V_{tb}|$

- Assume $|V_{td}|$, $|V_{ts}| \ll |V_{tb}|$
- Using $\sigma^{th} = 62.3^{+2.3}_{-2.4}\text{pb}$
- Unconstrained measurement:

$$|V_{tb}| = \sqrt{\frac{\sigma^{exp}}{\sigma^{th}}} = 1.16 \pm 0.22(exp) \pm 0.02(th)$$

- Constrained limit: $0 \leq |V_{tb}|^2 \leq 1$
  - 95% CL
  - 2D measurement: $|V_{tb}| > 0.63$
  - BDT measurement: $|V_{tb}| > 0.69$

Conclusion

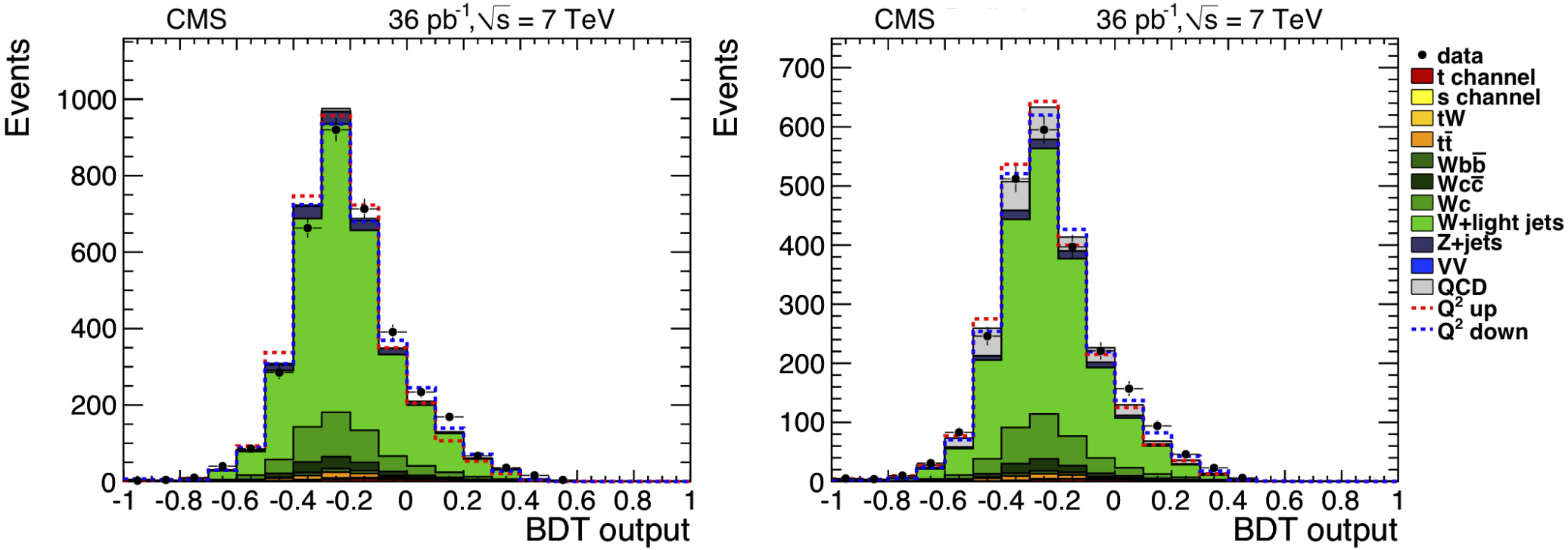
- Search for single top production in the *t* channel at CMS on full 2010 collision data
  - Small signal with large backgrounds (L ~ 36 pb^{-1})
  - Requires detailed understanding of the background and the detector
  - CMS-PAS-TOP-10-008, arxiv:1106.3052, to be published in Phys.Rev.Lett.
- 2 measurement methods used
  - Angular analysis (2D): Minimum model dependence
  - Multivariate analysis (BDT): Maximum sensitivity
- Results combined using BLUE method

$$\sigma = 83.6 \pm 29.8 \text{ (stat+syst)} \pm 3.3 \text{ (lumi) pb}$$

- Measurement being updated with 2011 data: $\mathcal{L} \sim 2$ fb^{-1} !
- Measurements in s and tW being done

Additional material

The *bdt* discriminant



bdt discriminant for the muon and electron channels in the W-enriched BDT selection (no b tagging)

- Simulation is scaled to the number of events in data. Also shown is the variation corresponding to varying Q^2 for the W/Z+X processes up and down by a factor of two.