Top quark measurements at CMS

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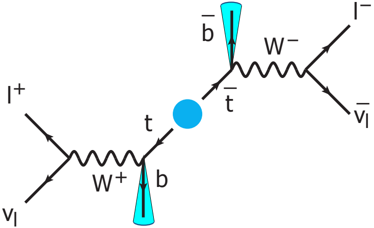
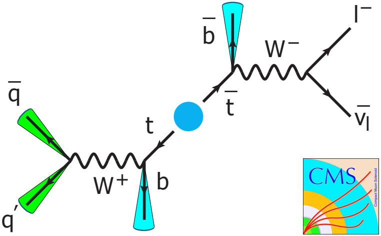
Overview

Di-lepton channel



Semi-leptonic/lepton+jets channel



Motivations:

- Chance to study the highest mass particle discovered so far at a much higher energy.
- Only way to study unbound quarks as it decays before it hadronises.
- The topology of top quarks makes use of the entirety of the detector.
- Top is a common background to searches for new physics.

Measurements with the 2010 Dataset

Cross-Section Measurements:

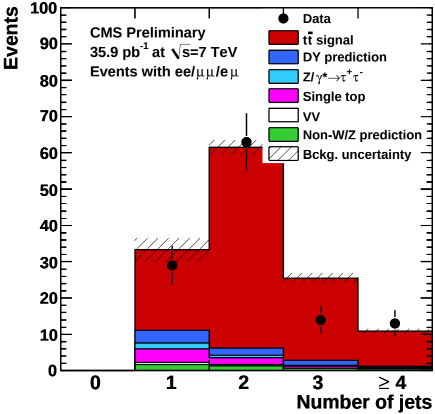
- Di-lepton channel with b-tagging. *TOP-10-005* and *TOP-10-001*
- Lepton+jets channel without b-tagging. *TOP-10-002*
- Lepton+jets channel with b-tagging. *TOP-10-003*
- Single-top t-channel. *TOP-10-008*

Other properties:

- Top mass in the di-lepton channel. *TOP-10-006*
- $\mathrm{t\bar{t}}$ invariant mass. *TOP-10-007*
- Charge asymmetry. *TOP-10-010*

The measurements use the full 2010 data $(36\mathrm{pb}^{-1})$. The results are available here:
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP

- Update to CMS TOP-10-001 (measurement with $3\ \mathrm{pb}^{-1}$).
- Considers e^+e^-, $\mu^+\mu^-$ and $e^\pm\mu^\mp$ channels.
- Di-lepton channel has a small branching ratio (6%) but also smaller backgrounds.
- Event counting experiment requiring at least two jets and one b-tag.
- Data driven estimates for Drell-Yan and other events with leptons.



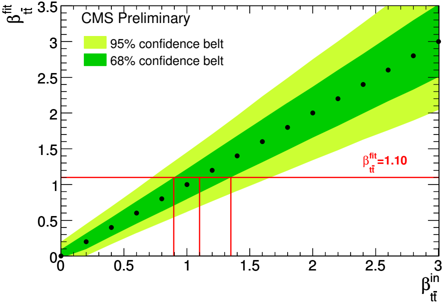
$$\boxed{\sigma_{t\bar{t}} = 168 \pm 18(\mathrm{stat}) \pm 14(\mathrm{syst}) \pm 7(\mathrm{lumi})\ \mathrm{pb}.}$$

$$\boxed{\sigma_{t\bar{t}}/\sigma_{Z/\gamma*} = 0.175 \pm 0.018(\mathrm{stat}) \pm 0.015(\mathrm{syst}).}$$

$t\bar{t}$ Cross-Section in the Lepton+Jets Channel without b-tagging (CMS TOP-10-002)

- Binned likelihood fit in the $\not{E}_T$ distribution for the three jet bin and in the M3 distribution for the four or more jet bin.
- M3 is the invariant mass of the three jets with the highest vectorialy summed p_T.
- The QCD templates are derived from data.
- Other templates from simulation.

Neyman construction



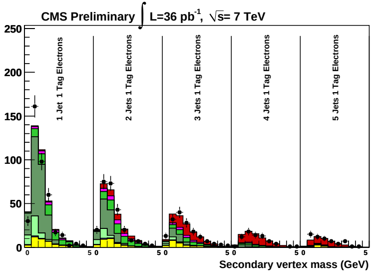
$$\beta_{t\bar{t}} = \frac{\sigma^{\mathrm{obs}}_{t\bar{t}}}{\sigma^{\mathrm{theory}}_{t\bar{t}}}$$

The dominant systematic uncertainty in this measurement is due to the jet energy scale.

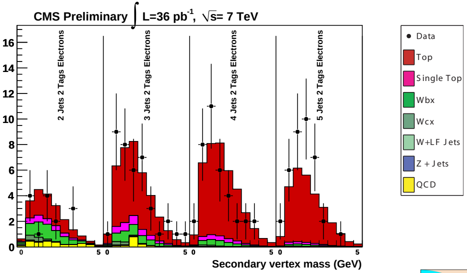
$$\boxed{\sigma_{t\bar{t}} = 173 \pm^{39}_{32} (\mathrm{stat} + \mathrm{syst}) \pm 7(\mathrm{lumi})\ \mathrm{pb.}}$$

$t\bar{t}$ Cross-Section in the Lepton+Jets Channel with b-tagging (CMS TOP-10-003)

- Binned maximum likelihood fit to the secondary vertex mass distribution.
- Fit simultaneously across one to five-inclusive jet bins and one to two or more tagged-jet bins.
- Simple b-tagger making use of the secondary vertex flight distance from the primary vertex.
- QCD templates and normalisation are derived from data, remaining backgrounds and signal templates are taken from simulation.



e+jets, 1 b-tag



e+jets, ≥ 2 b-tag

$t\bar{t}$ Cross-Section in the Lepton+Jets Channel with b-tagging (CMS TOP-10-003)

Source	Uncertainty (%)
Systematic uncertainties	
Lepton ID/reco/trigger	3
Unclustered $E_{\mathrm{T}}^{\mathrm{miss}}$ resolution	< 1
$t\bar{t}$+ Jets Q^2-scale	2
ISR/FSR	2
ME to PS matching	2
PDF	3.4
Profile likelihood parameters	
Jet energy scale and resolution	7.0
b tag efficiency	7.5
W+Jets Q^2-scale	9.1
Combined	11.6

The most significant systematic uncertainties are profiled in the fit.

This allows for their over all impact on the measurement to be reduced in comparison to the cross-check analyses in the backup.

$$\boxed{\sigma_{t\bar{t}} = 150 \pm 9(\mathrm{stat}) \pm 17(\mathrm{syst}) \pm 6(\mathrm{lumi})\ \mathrm{pb.}}$$

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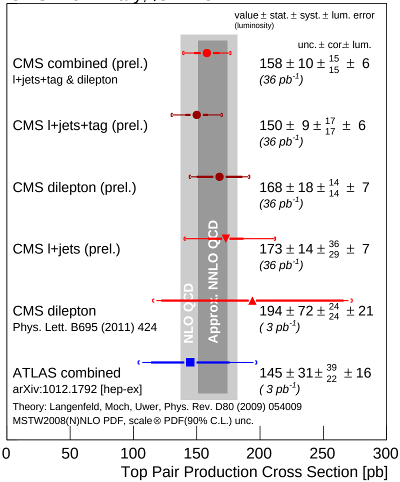
Combination of $t\bar{t}$ cross-section measurements (CMS-PAS TOP-11-001)

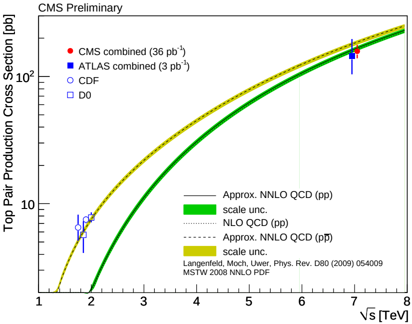
- Combination of di-lepton and lepton+jets with b-tagging cross-section measurements.
- Uses the "best linear unbiased estimator" (BLUE) technique.



$$\sigma_{t\bar{t}}(\mathrm{CMS}) = 158 \pm 19 \text{ pb.}$$

$$\sigma_{t\bar{t}}^{\mathrm{NLO}}(\mathrm{HATHOR}) = 160^{+22}_{-23} \text{ pb.}$$

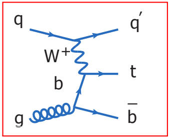
$$\sigma_{t\bar{t}}^{\mathrm{approx.\ NNLO}}(\mathrm{HATHOR}) = 164^{+10}_{-13} \text{ pb.}$$

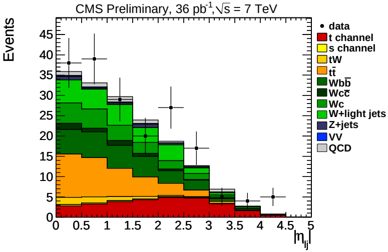


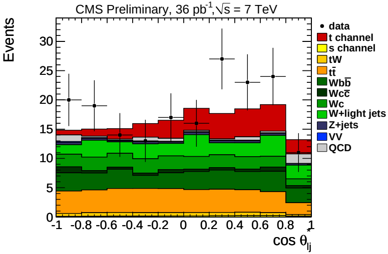
Single-top t-channel cross-section (CMS-PAS TOP-10-008)

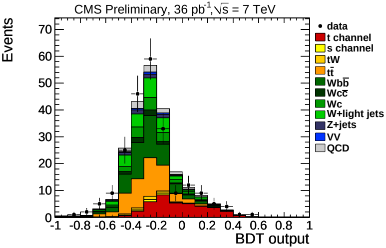
There are two complimentary analyses:

- A two dimensional unbinned likelihood fit to the pseudorapidity of the light jet and the cosine of the angle between the light jet and the lepton.
- A multivariate analysis using boosted decision trees.

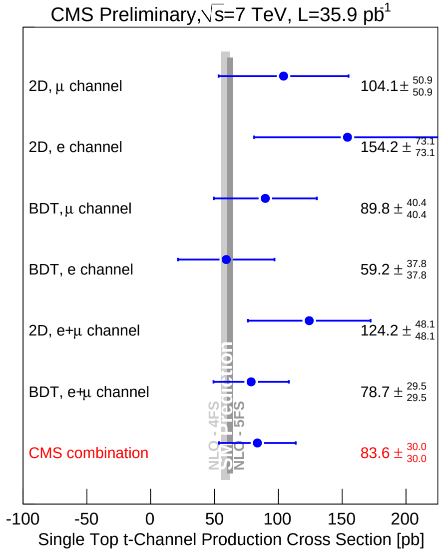








Single-top t-channel cross-section (CMS-PAS TOP-10-008)



Combined result using BLUE:

$$\boxed{\sigma_{\mathrm{t}} = 83.6 \pm 29.8(\mathrm{stat}+\mathrm{syst}) \pm 3.3(\mathrm{lumi})\ \mathrm{pb}.}$$

Theory:

$$\sigma_{t,4FS} = 59.1^{+3.0}_{-4.0}\ \mathrm{pb.}$$
$$\sigma_{t,5FS} = 62.3^{+2.3}_{-2.4}\ \mathrm{pb.}$$

Expected and observed signal significance

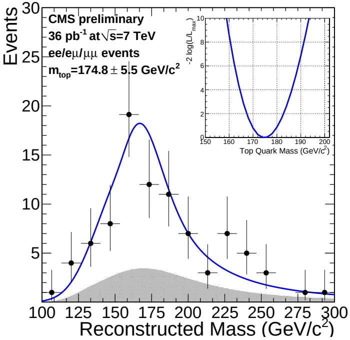
Analysis, channel	expected	observed
2D, μ-channel	$1.7^{+1.1}_{-1.0}$	2.5
2D, e-channel	$1.3^{+1.0}_{-1.1}$	3.1
2D, combined	$2.1^{+1.0}_{-1.1}$	3.7
BDT, μ-channel	$2.4^{+0.9}_{-1.0}$	3.1
BDT, e-channel	2.0 ± 1.0	1.9
BDT, combined	$2.9^{+1.0}_{-0.9}$	3.5

Top Quark Mass Measurement in the Di-lepton Channel (CMS-PAS TOP-10-006)

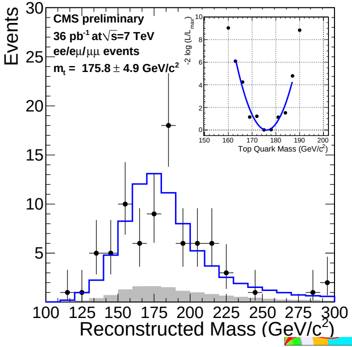
There are two analyses for measuring the top mass.

- The fully kinematic method (KINb).
- The analytical matrix weighting technique (AMWT).
- A likelihood fit is then performed to each distribution to extract the top mass with templates from simulation.

Kinematic method



AMWT method



● CMS Data
Background+signal model
Background model (shaded)

The inset shows the log-likelihood vs m_{top}

Top Quark Mass Measurement in the Di-lepton Channel (CMS-PAS TOP-10-006)

Systematic uncertainties in $\mathrm{GeV}/\mathrm{c}^2$

Source	KINb	AMWT	Correlation factor	Combination
jet energy scale	+3.1/-3.7	3.0	1	3.1
b-jet energy scale	+2.2/-2.5	2.5	1	2.5
Underlying event	1.2	1.5	1	1.3
Pileup	0.9	1.1	1	1.0
Jet-parton matching	0.7	0.7	1	0.7
Factorization scale	0.7	0.6	1	0.6
Fit calibration	0.5	0.1	0	0.2
MC generator	0.9	0.2	1	0.5
Parton density functions	0.4	0.6	1	0.5
b-tagging	0.3	0.5	1	0.4

Combined result using BLUE:

$$\boxed{m_{top} = 175.5 \pm 4.6(\mathrm{stat}) \pm 4.6(\mathrm{syst})\ \mathrm{GeV}/\mathrm{c}^2}$$

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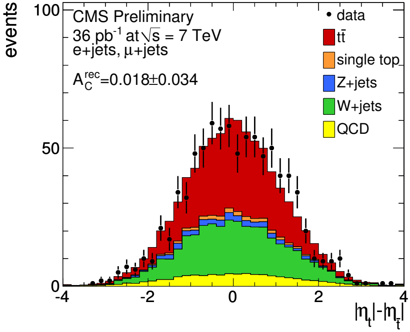
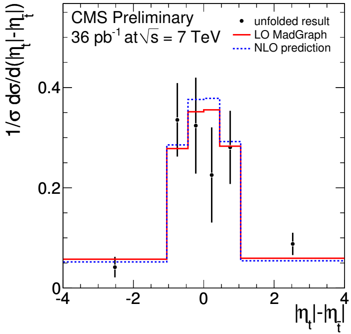
- Could be influenced by BSM effects (axigluons, Z', Kaluza Klein excitations...).
- CDF results currently show a 3.4σ deviation from the standard model prediction ($A_{FB} \sim 5\%$) for $m_{t\bar{t}} \geq 450~\mathrm{GeV/c^2}$.
- At the LHC the initial state is symmetric (pp collisions), so the pseudorapidity distributions should be symmetric about 0.
- The charge asymmetry will manifest as a difference in the width of the distribution so it is measured using $|\eta_t| - |\eta_{\bar{t}}|$.
- The asymmetry is predicted to be small, $A_C = 0.0130(11)$ [Ferrario, Rodrigo, et. al.].



Charge asymmetry measurement in the lepton+jets channel (CMS-PAS TOP-10-010)

Unfolded for detector effects



$$A_C = \frac{N^+ - N^-}{N^+ + N^-}$$

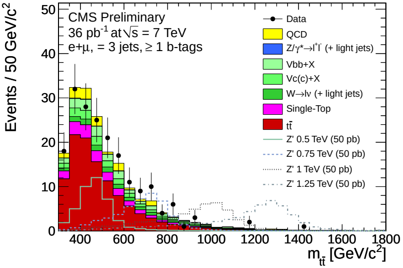
$$\boxed{A_C = 0.060 \pm 0.134(\mathrm{stat}) \pm 0.026(\mathrm{syst})}$$

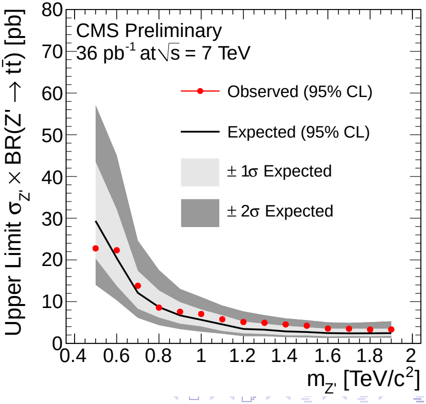
This analysis is currently statistically limited. With the same method it is expected that this will achieve similar sensitivity to the Tevatron results with $\sim 1\mathrm{fb}^{-1}$.

Search for Resonances in the $m(t\bar{t})$ distribution in the lepton+jets channel (CMS-PAS TOP-10-007)

- Search for Z' decaying to $t\bar{t}$ producing a narrow resonance (1% of its mass).
- QCD templates from data. Drell-Yan, $t\bar{t}$, single-top and other events with a leptonically decaying W are taken from simulation.
- Extract result with a log-likelihood fit.
- No evidence of new physics is visible from the 95% confidence limits.

≥ 3 Jets, 1 b-tag





Conclusion

With $36\mathrm{pb}^{-1}$ we have successfully:

- Measured $\sigma_{t\bar{t}}$ in the di-lepton and semi-leptonic channels with muons and electrons.
- Measured m_{top} in the di-lepton channel.
- Measured σ_{t} in t-channel production.
- Begun probing $m(t\bar{t})$ for narrow resonances from BSM effects.
- Begun measuring the charge asymmetry, A_C.

Results summary

$$\sigma_{t\bar{t}}(\mathrm{CMS}) = 158 \pm 19\ \mathrm{pb}$$

$$\sigma_{t} = 83.6 \pm 29.8(\mathrm{stat} + \mathrm{syst}) \pm 3.3(\mathrm{lumi})\ \mathrm{pb}$$

$$m_{top} = 175.5 \pm 4.6(\mathrm{stat}) \pm 4.6(\mathrm{syst})\ \mathrm{GeV/c^2}$$

$$A_C = 0.060 \pm 0.134(\mathrm{stat}) \pm 0.026(\mathrm{syst})$$

There is much more to come and a bright future for top physics at the LHC!

With thanks to Jasmin Grushke.

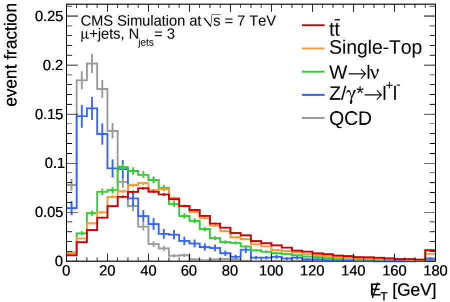
Backup

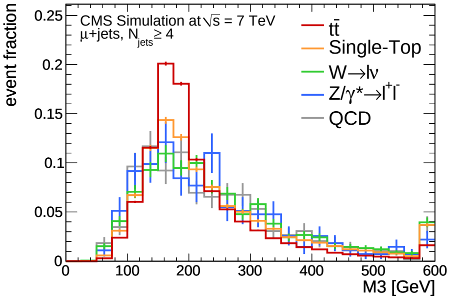
Systematics uncertainties (values in percent).

Source	$N_{\text{jet}} = 1$ $e^+e^- + \mu^+\mu^-$	$e^\pm\mu^\mp$	$N_{\text{jet}} \geq 2$ $e^+e^- + \mu^+\mu^-$	$e^\pm\mu^\mp$
Lepton selection	1.91/1.30	1.11	1.91/1.30	1.11
Energy scale	-3.0	-5.5	3.8	2.8
Lepton selection model	4.0	4.0	4.0	4.0
Branching ratio	1.7	1.7	1.7	1.7
Decay model	2.0	2.0	2.0	2.0
Event Q^2 scale	8.2	10	-2.3	-1.7
Top-quark mass	-2.9	-1.0	2.6	1.5
Jet and $\not{E}_T$ model	-3.0	-1.0	3.2	0.4
Shower model	1.0	3.3	-0.7	-0.7
Pileup	-2.0	-2.0	0.8	0.8
Subtotal (before tags)	11.2/11.1	13.1	8.0/7.9	6.2
b tagging (≥ 1 b tag)			5.0	5.0
Subtotal with tags			9.5/9.4	8.0
Luminosity	4	4	4	4

Additional Material for TOP-10-002

	$\beta_{t\bar{t}}$	N_{ST}	N_{W+jets}	N_{Z+jets}	N_{QCD} e+jets	N_{QCD} μ+jets
predicted	1.00	72 ± 4	1069 ± 77	138 ± 10	367 ± 27	58 ± 4
fitted	1.10	76 ± 22	1475 ± 86	184 ± 51	440 ± 44	113 ± 31





μ+jets channel

Additional Material for TOP-10-002

Electron+jets:

$$\sigma_{t\bar{t}} = 180^{+45}_{-38}(\mathrm{stat.} + \mathrm{syst.}) \pm 7(\mathrm{lumi.})\ \mathrm{pb}\,.$$

Muon+jets:

$$\sigma_{t\bar{t}} = 168^{+42}_{-35}(\mathrm{stat.} + \mathrm{syst.}) \pm 7(\mathrm{lumi.})\ \mathrm{pb}\,.$$

Combined:

$$\sigma_{t\bar{t}} = 173^{+39}_{-32}(\mathrm{stat} + \mathrm{syst}) \pm 7(\mathrm{lumi})\ \mathrm{pb}\ .$$

	stat.+syst. uncertainty	
Stat.+bkg. uncertainty	-8.4%	$+8.7\%$
JES	-17.6%	$+20.3\%$
JER	-8.4%	$+8.8\%$
ISR/FSR variation	-8.6%	$+9.0\%$
Factorization scale	-10.6%	$+11.2\%$
Matching threshold	-9.8%	$+10.5\%$
Branching ratio	-8.6%	$+8.9\%$
Efficiencies (from T&P)	-8.7%	$+9.2\%$
QCD rate & shape	-8.9%	$+9.1\%$
Lepton scale	-8.4%	$+8.7\%$
PDF uncertainty	-8.5%	$+8.7\%$
Pile-up	-9.3%	$+9.3\%$
Total	-19.3%	$+23.5\%$

- QCD template shape from none-isolated leptons.

Electron+jets:

$$\boxed{\sigma_{t\bar{t}} = 158 \pm 14\,(\mathrm{stat.}) \pm 19\,(\mathrm{syst.}) \pm 6\,(\mathrm{lum.})\ \mathrm{pb}}$$

Muon+jets:

$$\boxed{\sigma_{t\bar{t}} = 145 \pm 12\,(\mathrm{stat.}) \pm 18\,(\mathrm{syst.}) \pm 6\,(\mathrm{lum.})\ \mathrm{pb}}$$

Combined:

$$\boxed{\sigma_{t\bar{t}} = 150 \pm 9\,(\mathrm{stat.}) \pm 17\,(\mathrm{syst.}) \pm 6\,(\mathrm{lum.})\ \mathrm{pb}}$$

- QCD normalisation from $\not{E}_T < 20\ \mathrm{GeV}$ region.
- QCD template shape from none-isolated leptons.

Muon in jet:

- $\boxed{\sigma_{t\bar{t}} = 163 \pm 21(\text{stat.}) \pm 35(\text{syst.}) \pm 7(\text{lumi.})\ \text{pb}}$

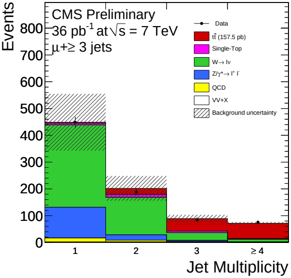
Neural-net muon-channel:

- $\boxed{\sigma_{t\bar{t}} = 151 \pm 15(\text{stat.})^{+35}_{-28}(\text{syst.}) \pm 6(\text{lumi.})\ \text{pb}}$

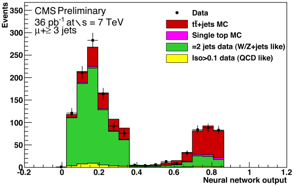
Electron-channel counting experiment:

- $\boxed{\sigma_{t\bar{t}} = 169 \pm 13(\text{stat.})^{+39}_{-32}(\text{syst.}) \pm 7(\text{lumi.})\text{pb}}$

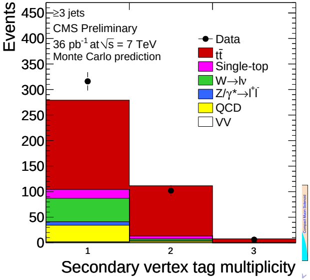
Muon-in-jet cross-check



Neural-net muon-channel cross-check



Electron-channel counting experiment cross-check



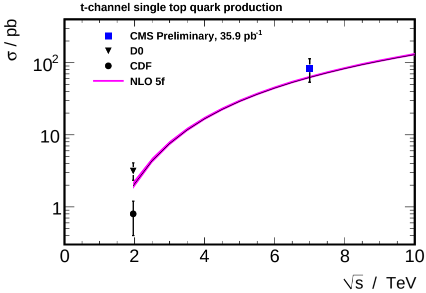
Additional theory results:

- $\sigma_{t\bar{t}}^{\mathrm{NLO}}(\mathrm{MCFM}) = 158^{+23}_{-24}$ pb ,
- $\sigma_{t\bar{t}}^{\mathrm{approx.NNLO}}(\mathrm{Kidonakis}) = 163^{+11}_{-10}$ pb ,

Table: Summary of measured top pair production cross sections for the lepton+jets channel and the di-lepton channel used in the cross section combination, also quoting the relative weights the individual measurements are assigned when extracting the combined value.

Measurement	Cross section [pb]	Weight
CMS l+jets+tag	$150 \pm 9(stat) \pm 17(syst) \pm 6(lumi)$	58%
CMS di-lepton	$168 \pm 18(stat) \pm 14(syst) \pm 7(lumi)$	42%

uncertainty	correlation	impact on 2D −	impact on 2D +	impact on BDT −	impact on 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:					
$t\bar{t}$ ($\pm14\%$)	100	$+2.0$	-1.9	$+0.5$	-0.6
single top s ($\pm30\%$)	100	-0.4	$+0.5$	-0.4	$+0.4$
single top tW ($\pm30\%$)	100	$+1.1$	-1.0	< 0.2	< 0.2
$Wb\bar{b}$, $Wc\bar{c}$ ($\pm50\%$)	100	-3.0	$+2.9$	$+1.7$	-1.9
Wc ($^{+100\%}_{-50\%}$)	100	-3.0	$+6.1$	-2.4	$+4.4$
Z+jets ($\pm30\%$)	100	-0.6	$+0.7$	$+0.4$	-0.2
electron QCD (BDT: $\pm100\%$, 2D: $^{+130\%}_{-100\%}$)	50	$+2.9$	-3.7	-1.7	$+1.7$
muon QCD (BDT: $\pm50\%$, 2D: $\pm50\%$)	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 ($\pm5\%$)	0	—	—	-1.4	$+1.4$
muon efficiency ($\pm5\%$)	0	—	—	-3.6	$+3.5$
V+jets ($\pm50\%$)	0	—	—	-1.5	< 0.2
2D-only uncertainties:					
muon W+light ($\pm30\%$)	0	-1.4	$+1.4$	—	—
electron W+light ($\pm20\%$)	0	-0.6	$+0.7$	—	—
W+light model uncertainties	0	-5.4	$+5.4$	—	—



Expected and observed signal significance

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

Kinematic method (KINb)

- Solve the kinematics equations describing the $\mathrm{t\bar{t}}$ system many times for each lepton-jet combination.
- Vary jet p_T, $\not{E}_T$ and $p_z^{\mathrm{t\bar{t}}}$ independently according to their resolutions.
- Choose solutions with lowest invariant mass, given $\Delta(m_{\mathrm{t}} - m_{\bar{\mathrm{t}}}) < 3\ \mathrm{GeV/c^2}$.

Analytical matrix weighting technique (AMWT)

- Obtain solutions for m_{top} in the range 100 to 300 $\mathrm{GeV/c^2}$.
- Assign a weight, w, to each solution given in the equation bellow.
- $F(x_i)$ is the parton distribution function.
- Parameters x_i correspond to Björken x values for the initial partons, with the summation being over each of the possible leading order initial parton states.
- $p(E*_l|m_{\mathrm{t}})$ is the probability of observing a charged lepton of energy $E*$ in the rest frame of the top-quark given a top mass m_t.

$$\boxed{w = \{\sum F(x_1)F(\bar{x_2})\}\, p(E^*_{\ell+}|m_t)p(E^*_{\ell-}|m_t)}$$

Table: Summary of the systematic uncertainties (in GeV/c^2) in the measurement of m_{top}, together with their correlations and combined values.

Source	KINb	AMWT	Correlation factor	Combination
jet energy scale	+3.1/-3.7	3.0	1	3.1
b-jet energy scale	+2.2/-2.5	2.5	1	2.5
Underlying event	1.2	1.5	1	1.3
Pileup	0.9	1.1	1	1.0
Jet-parton matching	0.7	0.7	1	0.7
Factorization scale	0.7	0.6	1	0.6
Fit calibration	0.5	0.1	0	0.2
MC generator	0.9	0.2	1	0.5
Parton density functions	0.4	0.6	1	0.5
b-tagging	0.3	0.5	1	0.4

Table: Summary of measured top quark mass for the KINb and AMWT methods with the contributing weights to the combined mass value.

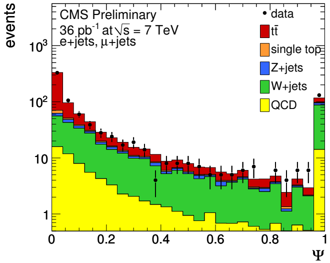
Method	Measured m_{top} (in GeV/c^2)	Weight
AMWT	$175.8 \pm 4.9(stat) \pm 4.5(syst)$	0.65
KINb	$174.8 \pm 5.5(stat)^{+4.5}_{-5.0}(syst)$	0.35
combined	$175.5 \pm 4.6(stat) \pm 4.6(syst)$	$\chi 2/N_{\mathrm{dof}}$=0.040 (p-value=0.84)

Reconstructing the $t\bar{t}$ final state

- Solve for z-component of neutrino in the leptonically-decaying W system under the assumption of the W pole mass ($80.4\ \mathrm{GeV/c^2}$).
- For each of the possible four jet combination, the quantity Ψ (defined below) is determined.
- The hypothesis with the smallest value of Ψ is chosen.

$$\boxed{\Psi = \chi^2(1 - P_b(x_{b_{had}}))(1 - P_b(x_{b_{lep}}))P_b(x_{q1})P_b(x_{q2})}$$

$$\boxed{\chi^2 = \frac{(m^{\mathrm{b.p.}}_{\mathrm{t,had}} - m^{\mathrm{rec}}_{\mathrm{t,had}})^2}{\sigma^2_{m_{\mathrm{t,had}}}} + \frac{(m^{\mathrm{b.p.}}_{\mathrm{t,lep}} - m^{\mathrm{rec}}_{\mathrm{t,lep}})^2}{\sigma^2_{m_{\mathrm{t,lep}}}} + \frac{(m^{\mathrm{b.p.}}_{\mathrm{W,had}} - m^{\mathrm{rec}}_{\mathrm{W,had}})^2}{\sigma^2_{m_{\mathrm{W,had}}}}}$$



Smearing between true and reconstructed $|\eta_t| - |\eta_{\bar{t}}|$

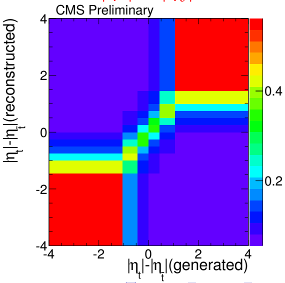
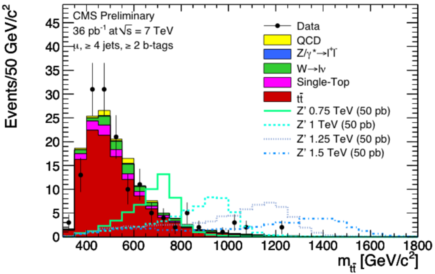


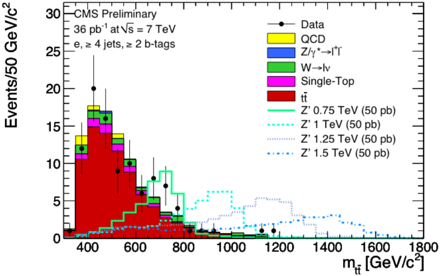
Table: List of systematic uncertainties taken into account in the measurement of A_C. Listed are the positive and negative shifts induced by systematics in ensemble tests. For systematics uncertainties which shift A_C in only one direction only the maximal shift in this direction is quoted.

source of systematic	positive shift in A_C	negative shift in A_C
jet energy scale	0.017	-
jet energy resolution	0.007	-0.006
Q^2 scale	0.003	-0.007
ISR/FSR	0.005	-0.0006
matching threshold	0.004	-0.006
PDF	0.004	-0.011
b tagging	0.007	-
lepton efficiency	0.017	-0.018
QCD model	0.005	-0.005
overall	$\pm$0.026	

Cross check analysis

- Entirely data-driven background estimation to reduce systematics from modelling.
- Different lepton-isolation which are less sensitive to the boost of the top quark.
- Different b-tagging algorithm.





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