Top Quark Pair Production Cross Sections at CMS



Andreas B. Meyer on behalf of the CMS Collaboration

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Motivation

- Top Quark is special
 - heaviest known particle
 - decay before hadronization: "bare quark"
 - maximum sensitivity to Higgs (EWK loop corrections)
- Precision measurements of SM parameters
 - total cross section, differential distributions
 - properties (mass, spin structure, asymmetries, couplings, V_{tb}...)
- Search for New Physics
 - New physics might preferentially couple / decay to top
 - non-standard couplings ?
- LHC is a top factory with multi TeV scale reach
 > 1 fb⁻¹ : > 160k top quark pairs produced in CMS









Gluon-Gluon Fusion











Dileptons (µe,ee,µµ)

2010: 36 pb⁻¹









Event Selection

≥2 jets

Inclusive single lepton triggers ($p_T > 15$ (22) GeV for $\mu(e)$)

- \geq 2 isolated, opposite charge leptons (ee,µµ,eµ)
 - p_T>20 GeV, |η|<2.4 (μ), 2.5 (e)
 - Lepton ID and conversion rejection efficiency: 99% for μ , 90% for e
 - Relative Isolation < 0.15

Dileptons (µe,ee,µµ)

2010: 36 pb⁻¹

arXiv: 1105.5661





- Backgrounds
 - Drell Yan (ee,μμ): estimated from data (using events at Z peak)
 - QCD, W+jets: estimated from data (using tight-to-loose ratio)
- Main systematics:



Background free sample of top quark pair events !

Dileptons (µe,ee,µµ)

2010: 36 pb⁻¹

arXiv: 1105.5661



9 separate measurements

	Final state	e ⁺ e ⁻	$\mu^+\mu^-$	$e^{\pm}\mu^{\mp}$
	At least two jets, no b-tagging requirement			
Cross section determination:	Events in data	23	28	60
	Simulated backgrounds	1.4 ± 0.3	1.5 ± 0.3	5.2 ± 1.2
 count number of events above background 	${ m Z}/\gamma^{\star} ightarrow { m e^+e^-}/\mu^+\mu^-$	3.0 ± 1.8	7.4 ± 4.1	-
	Non-W/Z	1.1 ± 1.4	0.6 ± 1.1	1.4 ± 1.6
3 categories for each mode (ee uu eu);	All backgrounds	5.5 ± 2.3	9.5 ± 4.3	6.7 ± 2.0
- 5 calegones for each mode (ee,µµ,eµ).	Total acceptance \mathcal{A} (%)	0.259 ± 0.021	0.324 ± 0.025	0.928 ± 0.057
1 jet no b-tagging	Cross section (pb)	$189 \pm 52 \pm 29$	$159 \pm 45 \pm 39$	$160 \pm 23 \pm 12$
i jet, no o tagging	east two jets, at le	ast one b-jet		
>2 jets, no b-tagging	Events in data	15	24	51
	Simulated backgrounds	0.7 ± 0.2	0.8 ± 0.3	2.5 ± 0.7
► >2 jets. \geq 1 b-tag	$Z/\gamma^{\star} \rightarrow e^+e^-/\mu^+\mu^-$	0.7 ± 0.7	2.6 ± 1.8	_
_ j · · · , _ · · · · · · · · · · · · · · ·	Non-W/Z	0.9 ± 1.2	0.3 ± 0.8	0.5 ± 1.1
	All backgrounds	2.3 ± 1.4	3.8 ± 2.0	3.0 ± 1.4
(1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1,				0.857 ± 0.068
$\sigma(pp \rightarrow tt) = 168 \pm 18 (stat.) \pm 14 (stat.)$	syst.) ± 7 (Iu	lm1.) pb_	$186 \pm 45 \pm 25$	$156 \pm 23 \pm 13$
$\sigma = -168 + 18(\text{stat}) + 14(\text{syst}) + 7(1)$	imi) nh 🚞	<u>,, /.g</u>	requirement	10
$O_{tt} = 100 \pm 10 (3000.) \pm 14 (3930.) \pm 1 (10)$		0	10 10	18
systematic uncertainty: ~9%	$Z(a^{\star}) a^{\dagger}a^{-}(u^{\dagger}u^{-})$	1.6 ± 0.4	1.9 ± 0.4	3.6 ± 0.9
	$\Sigma/\gamma \rightarrow e^+e^-/\mu^+\mu$	0.2 ± 0.3 0.2 ± 0.5	5.2 ± 4.5 01 \pm 0.4	- 12 - 12
	All backgrounds	0.3 ± 0.3	0.1 ± 0.4 71 ± 1 2	1.3 ± 1.3
	Total acceptance A (%)	2.1 ± 0.7 0.058 ± 0.007	7.1 ± 4.5 0.074 \pm 0.009	4.9 ± 1.0 0 183 \pm 0 024
	Cross section (ph)	0.050 ± 0.007 282 $\pm 135 \pm 45$	$107 \pm 110 \pm 163$	0.105 ± 0.024 $200 \pm 65 \pm 35$
	cross section (pb)	$202 \pm 150 \pm 45$	107 ± 119 ± 105	$200 \pm 00 \pm 30$

- Cross section ratio tt/Z:
 - cancellation of some of the exp.systematics, no luminosity uncertainty
 - anti-correlated PDF uncertainties in Z and tt

$$\frac{\sigma(\mathrm{pp} \to \mathrm{t}\bar{\mathrm{t}})}{\sigma(\mathrm{pp} \to \mathrm{Z}/\gamma^{\star} \to \mathrm{e}^{+}\mathrm{e}^{-}/\mu^{+}\mu^{-})} = 0.175 \pm 0.018 \,(\mathrm{stat.}) \pm 0.015 \,(\mathrm{syst.})$$



e/µ+jets



- Event selection:
 - single lepton triggers (2010 same as for dilepton analysis)
 - exactly one isolated lepton
 - electrons: p_T > 30 GeV, |η|<2.5, relative isolation<0.1, conversion rejection
 - muons: p_T > 20 GeV, |η|<2.1, relative isolation<0.05</p>
 - Jets: p_T>30 GeV, |η|<2.4
- Two independent analyses:
 - no b-tag: fit MET and M3 shapes as discriminator variables
 - with b-tag: secondary vertex algorithm, MET > 20 GeV





e/µ+jets (no b-tag) 2010: 36 pb⁻¹

arXiv: 1106.0902



- Simultaneous fit to templates of two distributions in two separate samples
 - N(jets) = 3: MET distribution: separates top quark pair signal from QCD, Z+jets
 - N(jets) ≥ 4: M3 distribution (maximum vectorial sum of 3 jets): signal peaks around top mass





e/µ+jets (b-tag)

2010: 36 pb⁻¹

CMS-TOP-10-003

- Binned template fit
 - secondary vertex mass and jet multiplicity
 - separately for 1 b-tag and 2 b-tag events
- Combined in-situ fit of systematic errors



N Jet Distribution









arXiv: 1106.0902

no b-tag



- Cross section from MET and M3
 - ratio W+jet/Z+jets (± 30% within theory pred.)
 - single top (±30% within theory prediction)
- Dominant systematic errors: Jet energy scale, W+jets Q²-scale
- 4 cross check analyses:

e/µ+jets

- counting experiment in µ+jets (B/G scaling)
- simultaneous fit to jet multiplicity and p_T(μ)
- fit to η(μ) exploiting W charge asymmetry
- µ+jets with cut on MET>20 GeV
- $\sigma_{\mathrm{t}\bar{\mathrm{t}}} = 173^{+39}_{-32}\,(\mathrm{stat.} + \mathrm{syst.}) \pm 7\,(\mathrm{lumi.})\,\mathrm{pb}$

systematic uncertainty: ~20%



- Cross section from SV mass and Jet multiplicity
 - QCD bg (±100% within theory prediction)
 - single top and Z+jets (±30% within theory)
- Dominant systematic errors: Jet energy scale, b-tag, W+jets Q²-scale
- 3 cross check analyses
 - soft muon tagging in μ+jets
 - counting experiment in e+jets (B/G scaling)
 - neural net with track counting b-tag

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

systematic uncertainty: 12%

Hadronic Channel

- Event Selection:
 - Jets (anti-K_T using R = 0.5) within |η|<2.4
 - \geq 6 jets with:
 - 4 jets with p_T > 60 GeV
 - +1 jet with p_T > 50 GeV
 - +1 jet with p_T > 40 GeV
 - additional jets considered if p_T > 30 GeV
 - ≥2 b-tagged jets (high purity):
 - secondary vertex: N_{tracks} ≥ 3
 - decay length significance d_B > 2.0 (efficiency 38%, mis-tag 0.12%)
 - W from all non-b-tagged jets (m_W = 80.4 GeV)
 - reconstruct m(t) from bW pairs (mt = mtbar)
 - select the one combination with minimal χ^2
 - accept event if P(χ²) > 1%







- Cross section extract and a section extract and a section extract and a section extract and a section and a section
 - signal shape from sin
 - QCD background sha
 - using signal free (
 - weight non-b-tagg and η to distributikinematic fit
 - systematics: 50% (±5%)
- Dominant systematics
 - b-tagging (~16%)
 - jet energy scale (~14%)
 - background (~12%)



 $\sigma_{t\bar{t}} = 136 \pm 20 \text{ (stat.)} \pm 40 \text{ (sys.)} \pm 8 \text{ (lumi.) pb}$

systematic uncertainty: 29%



 $m_{top} (GeV/c^2)$



Hadronic Channel (Cross Check)

- Event Selection
 - same as main selection: ≥6 jets with:
 - 4 jets with p_T > 60 GeV
 - +1 jet with p_T > 50 GeV
 - +1 jet with pT > 40 GeV
 - veto against more than 8 jets with p_T > 30 GeV
 - ≥2 loose b-tags (b-tag track counting algorithm)
- Neural Network (NN_{out} > 0.65)
 - 8 input variables: ΣΕ_T, Σ₃E_T, Centrality (ΣΕ_T/√ŝ), Aplanarity , Sphericity, E_T^{*1,2,} <E_T*>_{3-Njet}
- Kinematic Fit

 - ΔR (b-tags) ≥ 1.2
- Signal fraction from binned max.LL fit to top mass of kinematic fit: 40.3%

$$\sigma_{t\bar{t}} = 157 \pm 30 \text{ (stat.)} \pm 47 \text{ (sys.)} \pm 9 \text{ (lumi.) pb}$$
(cross check result)
CMS preliminary, 1.1 f
Andreas B. Meyer

V/c⊻

CMS preliminary, 1.09 fb⁻¹ at $\sqrt{s} = 7$ TeV

CMS-TOP-11-007

2011: 1.09 fb⁻¹



Dilepton (μτ)

- 1 isolated muon
 - veto against additional isolated µ or e
 - p_T>20 GeV, |η| < 2.1
 - Iepton-jet separation: ΔR > 0.3
- ≥ 2 jets
 - p_T>30 GeV, |η|<2.4</p>
- MET> 40 GeV
- ≥1 b-tag
- = 1 τ-jet
 - p_T>20 GeV, |η|<2.4, (opp. lepton charge)</p>
 - tau identification τ-jet from hadrons and π⁰-strips in a cone ΔR=2.8/p_T
 - charged hadrons (standard Particle Flow)
 - π^0 reconstructed in narrow η - ϕ 'strips' in ECAL, taking into account photon conversion





Top Quark Pair Production Cross Sections at

2011 data: 1.09 fb⁻¹

CMS-TOP-11-006

18

Dilepton (μτ)

2011 data: 1.09 fb⁻¹ CMS-TOP-11-006

^zake Rate

- Cross section extraction: count N_{events} above bg
- Backgrounds:
 - τ-fake (estimated from data)
 - mostly from W+jets and tt \rightarrow I+jets
 - W+ ≥1-jet and multi-jet QCD samples
 - the genuine τ-contribution (18%) within these τ-fake study samples are taken from MC
 - other sources of background (estimated from MC)
 - $Z \rightarrow \tau^+ \tau^-$
 - single top
- Dominant systematics
 - **τ-fake rate**
 - Jet energy scale
 - b-tagging

 $\sigma_{t\bar{t}}^{\tau-dil} = 148.7 \pm 23.6 (stat.) \pm 26.0 (syst.) \pm 8.9 (lumi.) \text{ pb}$

systematic uncertainty: 18%





Top Quark Pair Production Cross Sections at CMS

Combined Results

CMS-TOP-11-001





Top Quark Pair Production Cross Sections at CMS





- CMS has already performed a full suite of tt cross section measurements
- Good agreement with theory, no significant deviations from expectations
- Precision of data already starting to constrain predictions (QCD scales and PDF)
- Two experimentally challenging channels have been measured for the first time (using complete summer 2011 statistics)
 - dilepton channel μτ

results made possible by excellent CMS detector performance and understanding

- fully hadronic channel
- Upcoming top pair cross section measurements:
 - next level of precision
 - differential distributions
 - limited by systematics such as jet energy scale, b-tag, theory uncertainties

