Inclusive $t\bar{t}$ Cross-Section Measurements with CMS at 7, 8, and 13 TeV

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On behalf of the CMS collaboration

Top2015
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$t\bar{t}$ Cross-Sections

Why inclusive cross-sections?

- Precision test of SM, such as NNLO QCD calculations
- $t\bar{t}$ pair production important background in almost all other analyses
- Can be used to extract information on other quantities (ex. m_t, α_s)
- Sensitive to BSM physics

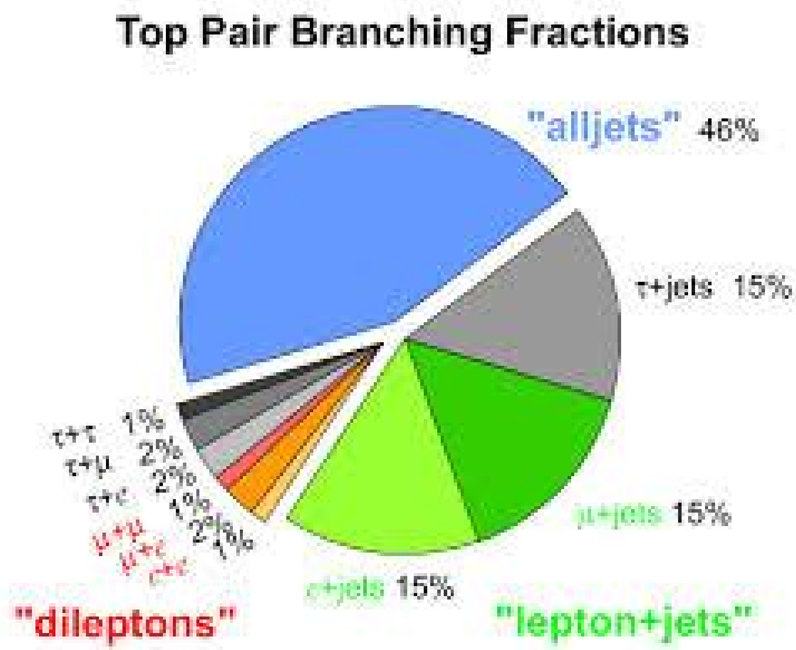
$\sqrt{s}$ (TeV)	$\sigma_{t\bar{t}}(NNLO + NNLL)$ [pb]
	m_t =172.5 GeV
7	$177.3^{+4.7}_{-6.0}(scale) \pm 9.0(PDF + \alpha_s)$
8	$252.9^{+6.4}_{-8.6}(scale) \pm 11.7(PDF + \alpha_s)$
13	$832^{+20}_{-29}(scale) \pm 35(PDF + \alpha_s)$

Fewer Leptons

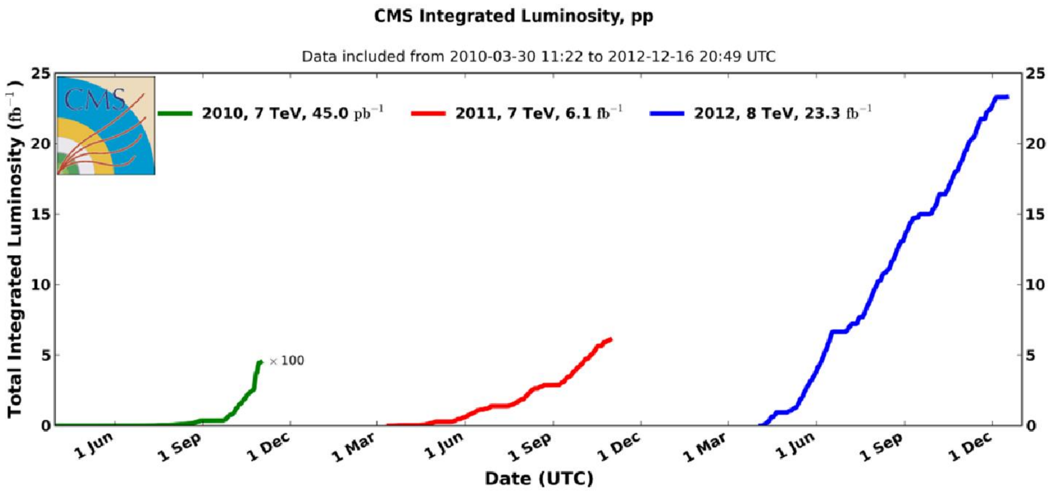
More Leptons

More Background

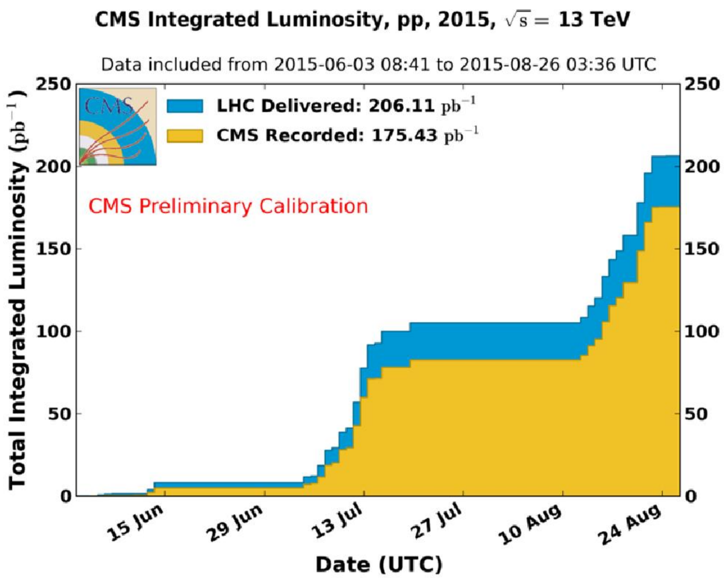
More information lost to neutrinos

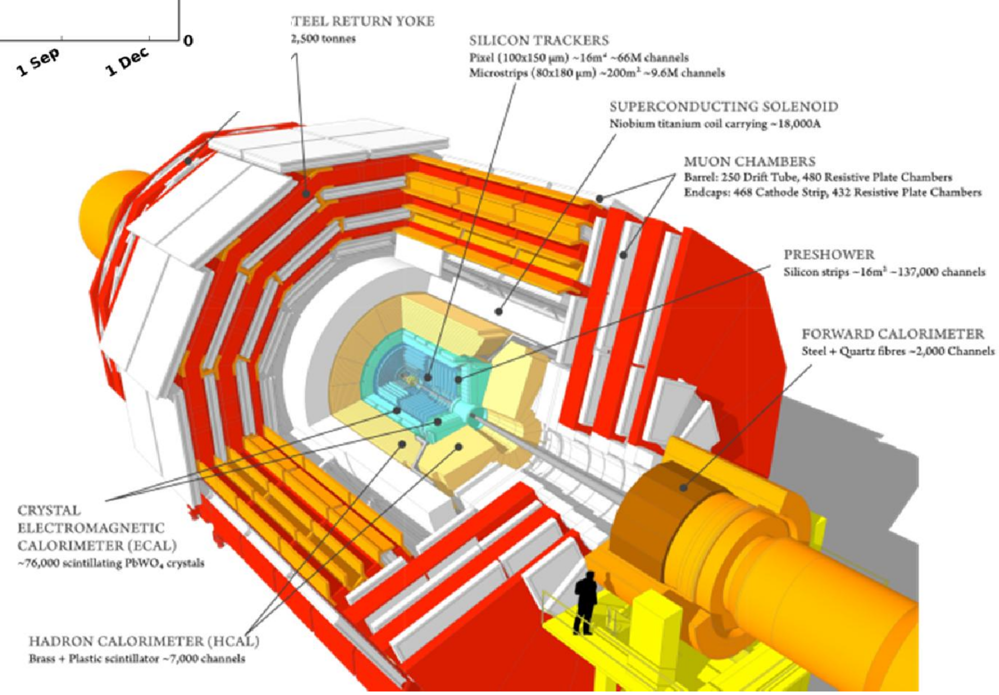


The CMS Detector and Luminosity



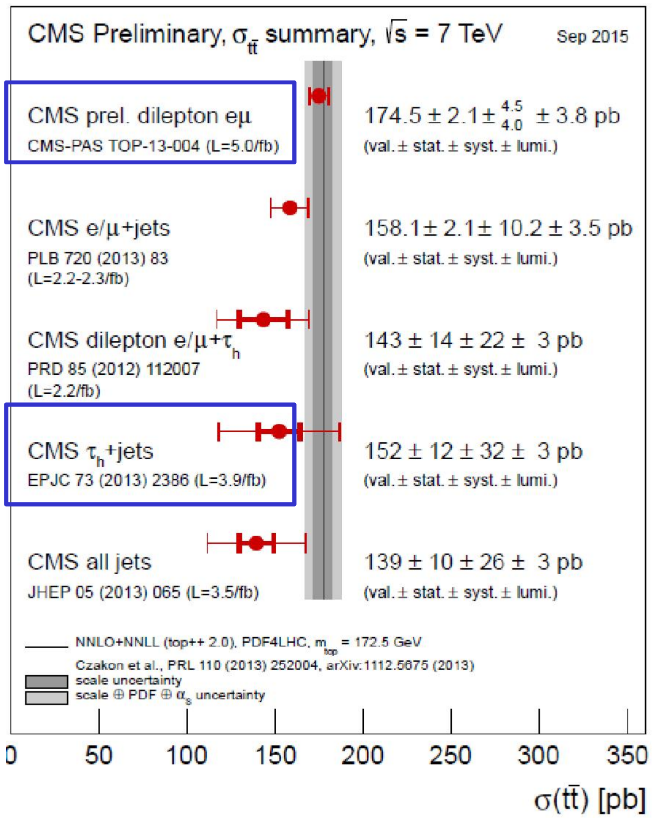
Contaminants in cryogenic system of solenoid initially limited the continuous up-time of the magnet in 50ns data-taking.



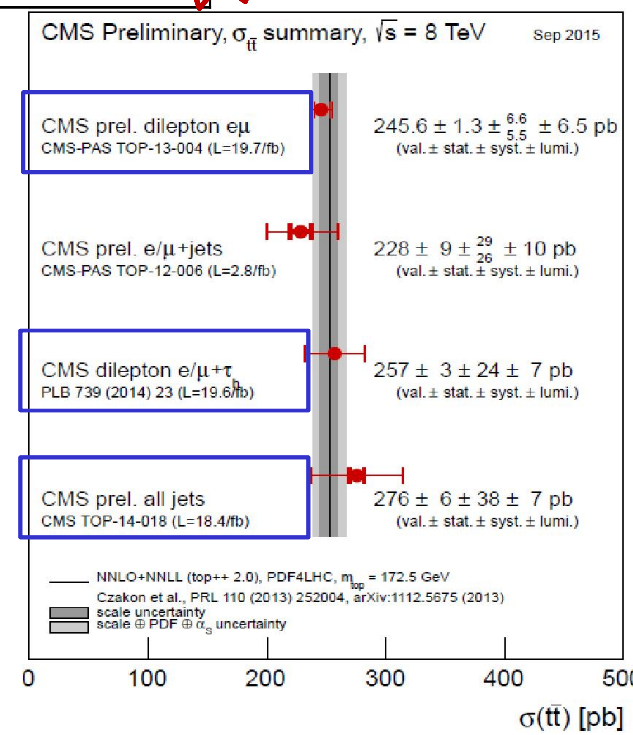


Analysis Overview

$\sqrt{s}$ (TeV)	luminosity	channel
8	18.4 fb^{-1}	all-jets New!
7	3.54 fb^{-1}	τ_h + jets
13	42 pb^{-1}	ℓ + jets New!
8	19.6 fb^{-1}	τ_h + e or μ
7+8	5+19.6 fb^{-1}	dilepton New!
13	42 pb^{-1}	dilepton New!



Measurements in previous datasets show good agreement with QCD predictions.



Many measurements have been performed—only a fraction presented here.

$\tau_h + jets$ Channel

arXiv:1301.5755

7 TeV
3.9 fb^{-1}

Trigger: dedicated multijet+τ_h trigger

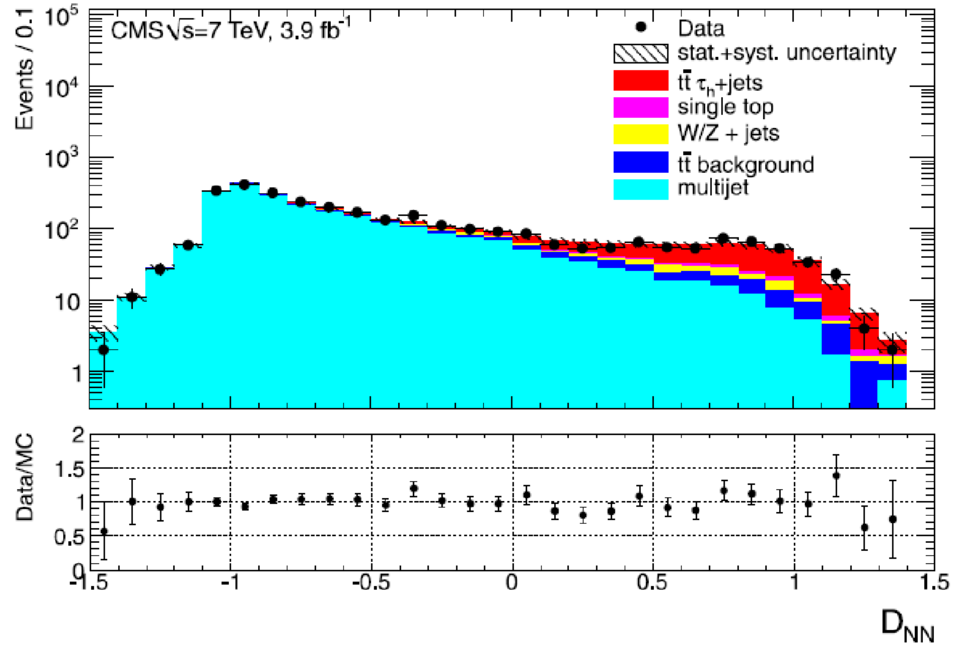
Signature:

- ≥ 4 jets with $p_T >$ (45,45,45,20) GeV
- ≥ 1b-tag (working point 60% efficient with mistag rate of 1%)
- 1 isolated $\tau_h$candidate, reconstructed with hadron-plus-strips (HPS) algorithm

Background: shape from multijet data events without b-tags

Use ANN to create discriminator

Binned negative log-likelihood fit



$$\sigma_{t\bar{t}} = 152 \pm 12(stat.) \pm 32(syst.) \pm 3(lum.)pb$$

Jet Energy Scale	11 %
τ_h identification	9 %
τ_h energy scale	7 %
Total systematic	21 %
Total statistical	8 %
Luminosity	2 %

arXiv:1407.6643

8 TeV
19.6 fb^{-1}

Lepton + τ_h Channel

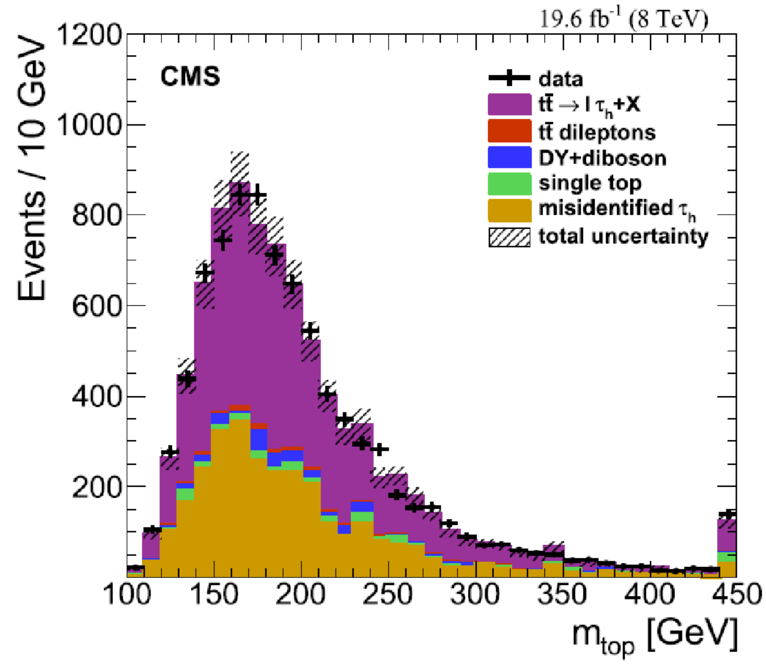
Trigger: single electron/muon

Signature:

- 1 isolated e(μ) with p_T>35(30) GeV
- ≥ 3 jets with p_T> (30,30,20) GeV
- ≥ 1 b-tag (working point 60% efficient with mistag rate of 0.1%)
- 1 τ_h candidate reconstructed with HPS with p_T> 20 GeV
- ${E_T}^{miss}$ > 40 GeV

Use KINb to calculate possible m_t values for additional separation

Channels combined with BLUE



$$\sigma_{t\bar{t}}(e\tau_h) = 255 \pm 4\,(\text{stat.}) \pm 24\,(\text{syst.}) \pm 7\,(\text{lum.})\ \text{pb}$$
$$\sigma_{t\bar{t}}(\mu\tau_h) = 258 \pm 4\,(\text{stat.}) \pm 24\,(\text{syst.}) \pm 7\,(\text{lum.})\ \text{pb}$$
$$\sigma_{t\bar{t}}(\text{combined}) = 257 \pm 3\,(\text{stat.}) \pm 24\,(\text{syst.}) \pm 7\,(\text{lum.})\ \text{pb}$$

τ_h Identification	6%
τ_h Mis-Identifcation	4.3%
Factorization Scale	2.9%
Total systematic	9.5%
Total statistical	1%
Luminosity	2.6%

All-Jets Channel: Method

New!

CMS-TOP-14-018
(to be submitted)

8 TeV
18.4 fb^{-1}

Trigger: multijet trigger

Signature:

- ≥ 6 jets with $p_T >$(60,60,60,60,40,40) GeV
- ≥ 2 *b*-tags (working point is 70% efficient with 1.4% mistag rate)

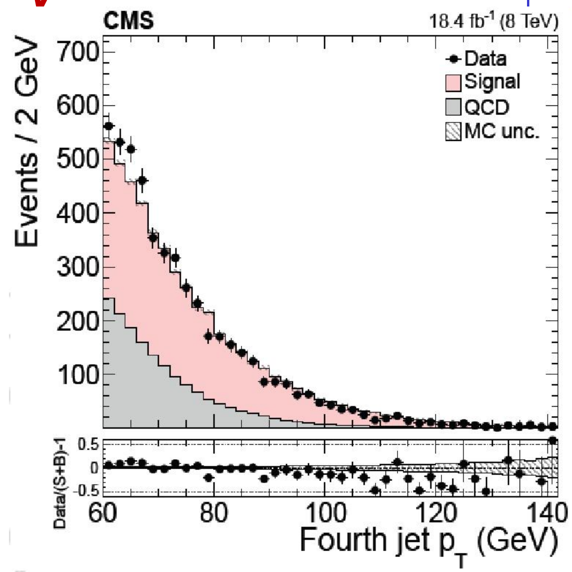
Kinematic fit:

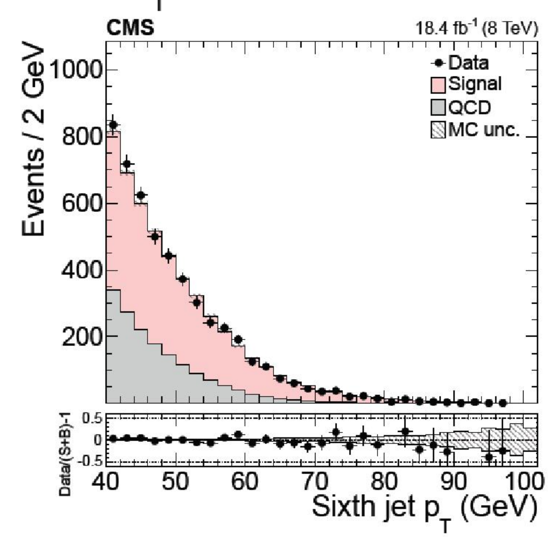
- perform χ^2 fit to fix jet-parton assignment
- allow jet four-momenta to vary within p_T and angular uncertainties, and impose $m_W = 80.4$ GeV and $m_t = m_{\bar{t}}$
- Require $P(\chi^2) >$0.15 and $\Delta R_{bb>}$2.0

Background:

- QCD multijet background only non-neglible contributor
- shape taken from multijet data events where events containing b-tagged jets are vetoed

Unbinned maximum likelihood fit to $m_t{}^{rec}$ to extract signal and background normalizations

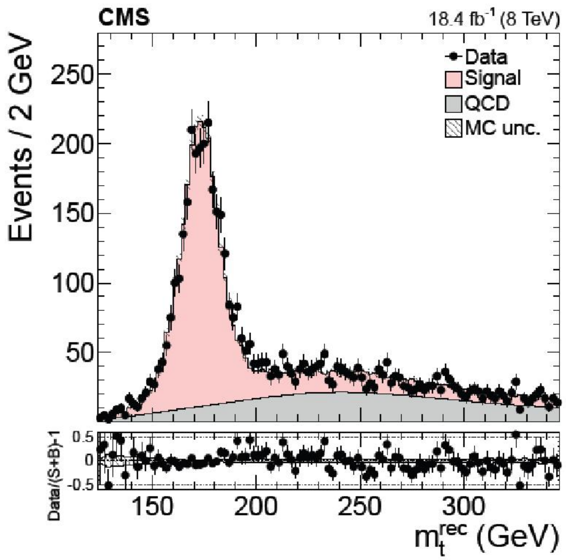


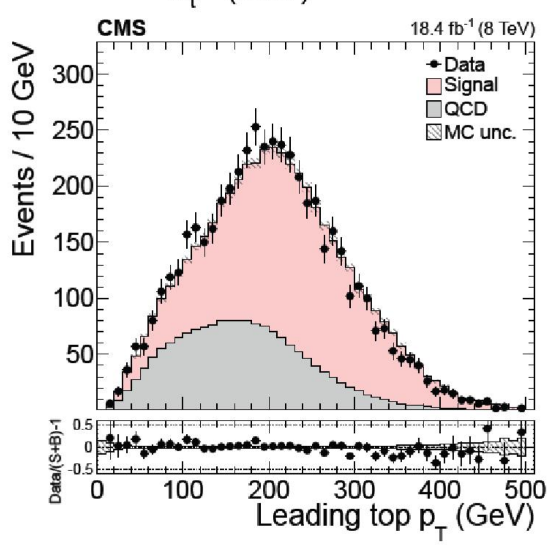


CMS-TOP-14-018
(to be submitted)

8 TeV
18.4 fb^{-1}

All-Jets Channel: Results





$$\sigma_{t\bar{t}} = 275.6 \pm 6.1(\text{stat.}) \pm 37.8(\text{syst.}) \pm 7.2(\text{lumi.})\ \text{pb}$$

Source	
Background modeling	±4.9%
JES	−7.0, +6.8%
JER	±3.5%
b tagging	±7.3%
Trigger efficiency	−2.2, +2.0%
Underlying event	±4.4%
Matching partons to showers	−4.2, +2.4%
Factorization and renormalization scales	−0.5, +3.8%
Color reconnection	±1.4%
Parton distribution function	±1.5%
Hadronization	±2.0%
Total systematic uncertainty	±13.6%
Statistical uncertainty	±2.3%
Integrated luminosity	±2.6%

Dilepton Channel: Method

New!

7 TeV
5.0 fb^{-1}

8 TeV
19.7 fb^{-1}

Trigger: dilepton (*eμ*) trigger

CMS-PAS-TOP-13-004

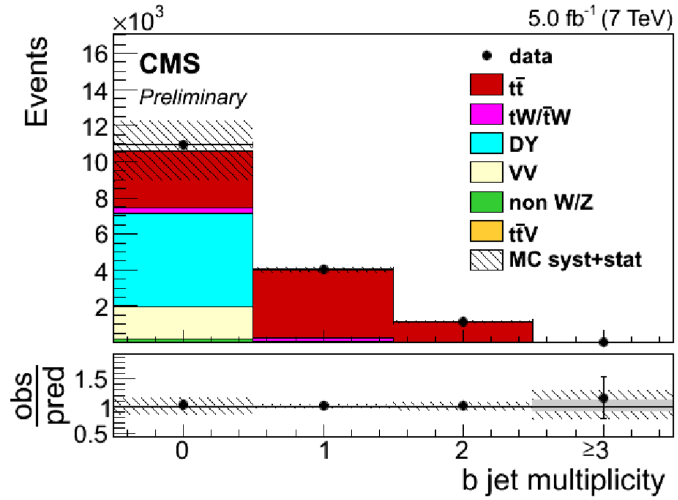
Signature: (note: no cut is made on number of jets!)

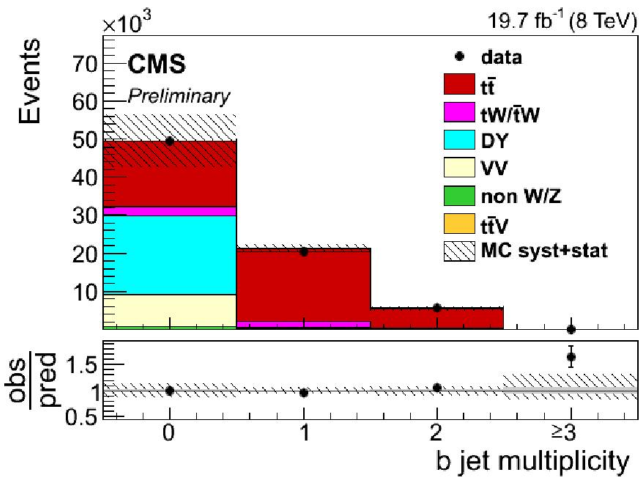
- OS isolated eμ pair with p_T>20 GeV
- jets have p_T> 30 GeV; b-jets are tagged with 60% efficiency and 0.1% mistag rate

Extended binned likelihood fit; signal modeled with Poisson terms with expected events:

$$s_1 = \mathcal{L}\sigma_{t\bar{t}}^{vis}\epsilon_{e\mu} \cdot 2\epsilon_b(1 - C_b\epsilon_b)$$
$$s_2 = \mathcal{L}\sigma_{t\bar{t}}^{vis}\epsilon_{e\mu} \cdot \epsilon_b^2 C_b$$
$$s_0 = \mathcal{L}\sigma_{t\bar{t}}^{vis}\epsilon_{e\mu} \cdot (1 - 2\epsilon_b(1 - C_b\epsilon_b) - C_b\epsilon_b^2)$$

Nuisance parameters are modeled by 2nd order polynomial, linear, or box priors



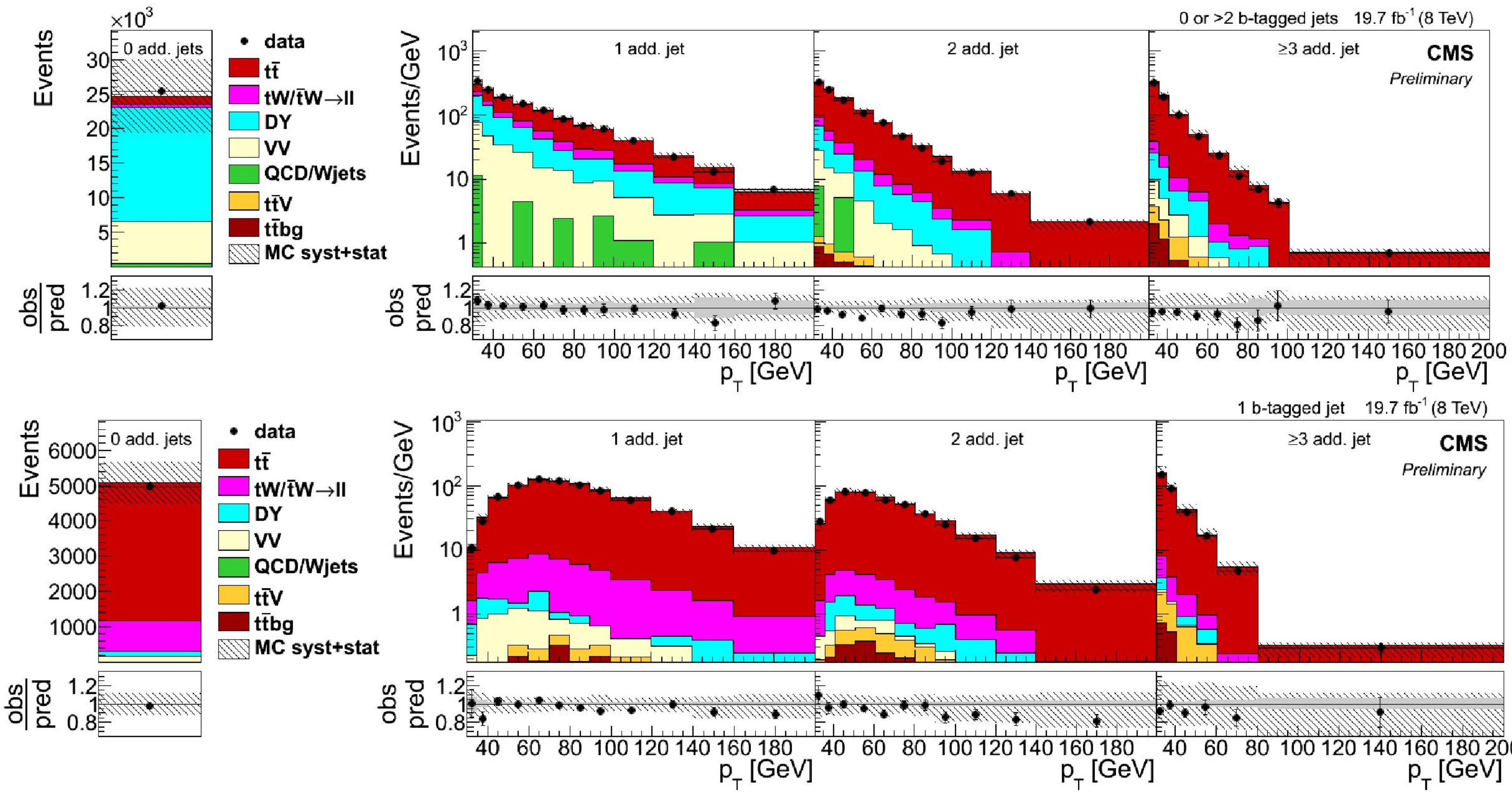


CMS-PAS-TOP-13-004

7 TeV	8 TeV
5.0 fb^{-1}	19.7 fb^{-1}

Dilepton Channel: Method

Jet p_T distributions allow fit to constrain systematics related to gluon radiation, jet energy scale, etc.



CMS-PAS-TOP-13-004

Dilepton Channel: Results

7 TeV
5.0 fb^{-1}

8 TeV
19.7 fb^{-1}

$$\sigma_{t\bar{t}} = \frac{\sigma^{vis}_{t\bar{t}}}{A_{e\mu}}$$

$$\sigma^{vis}_{t\bar{t}} = 3.05 \pm 0.04\,(\text{stat}) \pm^{0.08}_{0.07}\,(\text{syst}) \pm 0.07\,(\text{lumi})\,\text{pb} \quad \text{at } \sqrt{s} = 7\,\text{TeV and}$$
$$\sigma^{vis}_{t\bar{t}} = 4.24 \pm 0.02\,(\text{stat}) \pm^{0.11}_{0.10}\,(\text{syst}) \pm 0.11\,(\text{lumi})\,\text{pb} \quad \text{at } \sqrt{s} = 8\,\text{TeV}.$$

$$\sigma_{t\bar{t}} = 174.5 \pm 2.1\,(\text{stat}) \pm^{4.5}_{4.0}\,(\text{syst}) \pm 3.8\,(\text{lumi})\,\text{pb} \quad \text{at } \sqrt{s} = 7\,\text{TeV and}$$
$$\sigma_{t\bar{t}} = 245.6 \pm 1.3\,(\text{stat}) \pm^{6.6}_{5.5}\,(\text{syst}) \pm 6.5\,(\text{lumi})\,\text{pb} \quad \text{at } \sqrt{s} = 8\,\text{TeV}.$$

Source	Uncertainty (%)	
	7 TeV	8 TeV
Trigger	1.2	1.2
Lepton ID/Isolation	1.4	1.5
Jet Energy Scale	0.7	0.9
Total Systematic	+2.7 -2.3	+2.7 -2.5
Luminosity	2.1	2.6
Total Statistical	1.2	0.6

Extensions

- Extraction of top quark pole mass (see top mass session tomorrow!)
- Stop quark limits (see top and exotica session Thursday!)

Dilepton Channel: Method

New!

CMS-PAS-TOP-15-003

13 TeV
$42\ pb^{-1}$

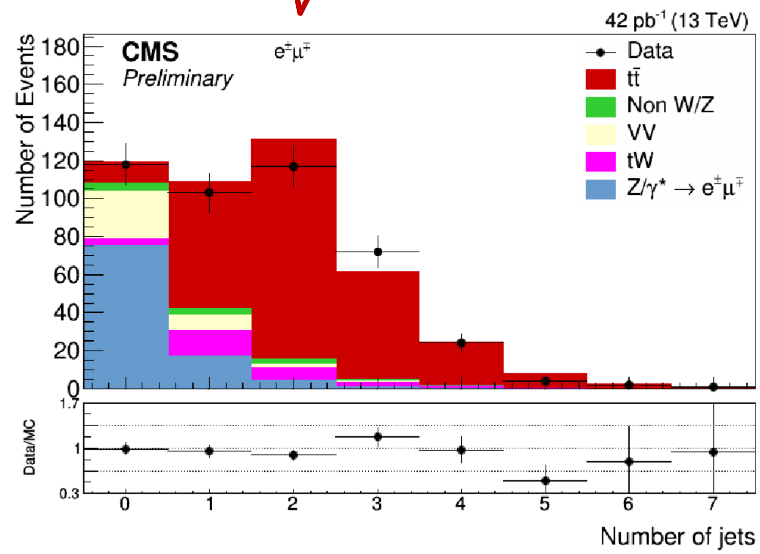
Trigger: dilepton ($e\mu$) trigger

Signature:

- Isolated OS $e\mu$ pair, $p_T > 20$ GeV
- ≥ 2 jets, $p_T > 30$ GeV, no b-tagging!
- $m_{ll} > 20$ GeV

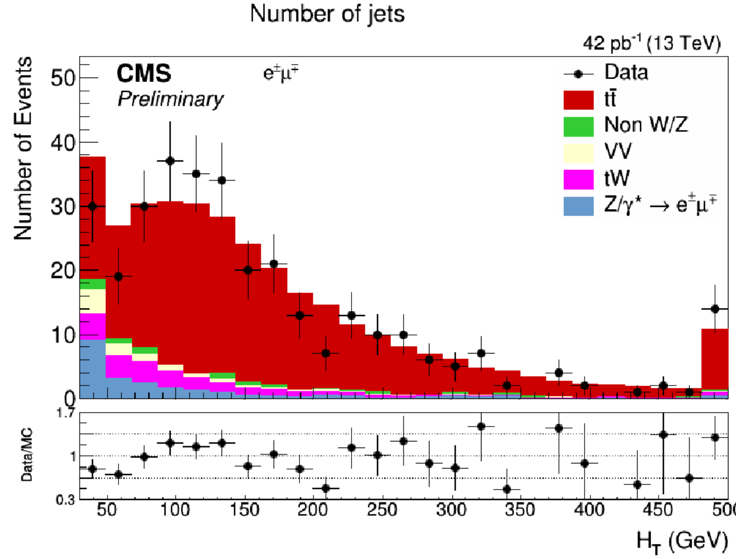
Backgrounds:

- DY from $R_{out/in}$ method
- Non-W/Z from SS control region
- Single t/VV from MC



Cut and Count

Source	Number of events $e^{\pm}\mu^{\mp}$
Drell–Yan	6.4 ± 1.2
Non-W/Z leptons	8.5 ± 4.3
Single top quark	10.6 ± 3.4
VV (V = W or Z)	2.6 ± 0.9
Total background	28.1 ± 5.7
$t\bar{t}$ dilepton signal	207 ± 16
Data	220



Dilepton Channel: Results

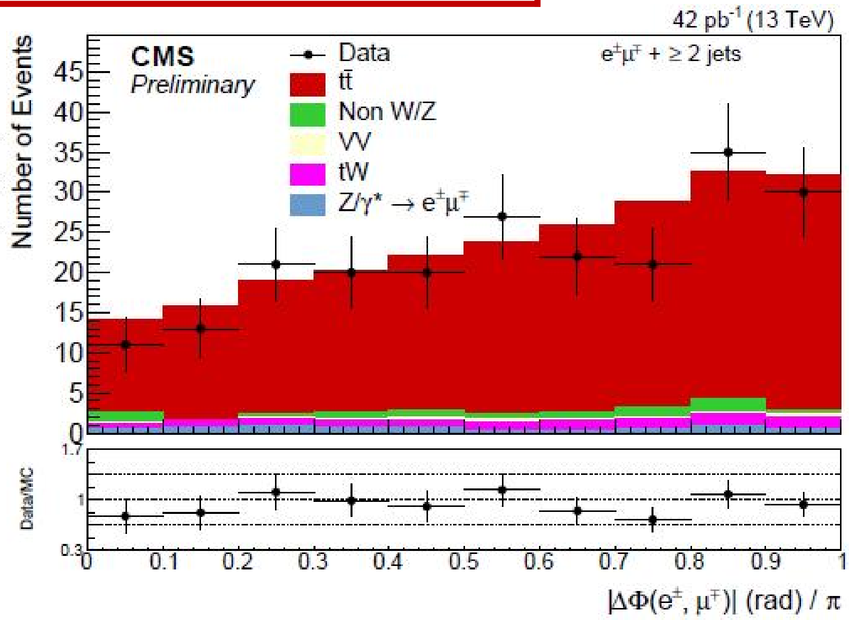
CMS-PAS-TOP-15-003

13 TeV
$42\ pb^{-1}$

$\sigma_{t\bar{t}} = 772 \pm 60(stat) \pm 62(syst) \pm 93(lumi)pb$ (total)

$\sigma_{t\bar{t}} = 12.9 \pm 1.0(stat) \pm 1.1(syst) \pm 1.5(lumi)$pb (fiducial)

Source	$\Delta\sigma_{t\bar{t}}$ (pb)	$\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ (%)
Data statistics	60	7.7
Trigger efficiencies	39	5.0
Lepton efficiencies	33	4.3
Lepton energy scale	< 1	≤ 0.1
Jet energy scale	20	2.6
Jet energy resolution	< 1	≤ 0.1
Pileup	2.8	0.4
Scale (μ_F and μ_R)	1.5	0.2
$t\bar{t}$ NLO generator	15	1.9
$t\bar{t}$ hadronization	14	1.8
PDF	12	1.5
Single top quark	14	1.8
VV	3.5	0.5
Drell–Yan	3.9	0.5
Non-W/Z leptons	8	1.0
Total systematic (no integrated luminosity)	62	8.0
Integrated luminosity	93	12
Total	126	16.4



Dependence on top quark mass was measured; increasing to $m_t = 173.34\ GeV$ decreases $\sigma_{t\bar{t}}$ by ~0.7%.

ℓ+jets Channel: Method

New!

CMS-PAS-TOP-15-005

13 TeV
$42\ pb^{-1}$

Trigger: single lepton triggers

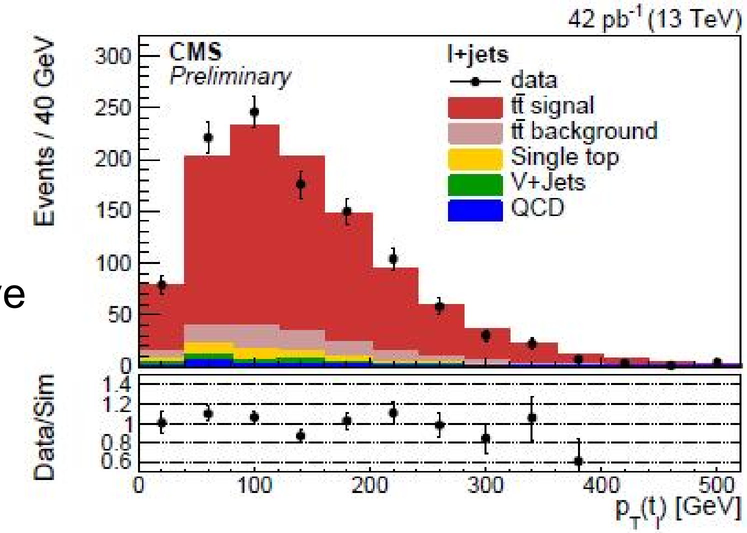
Signature

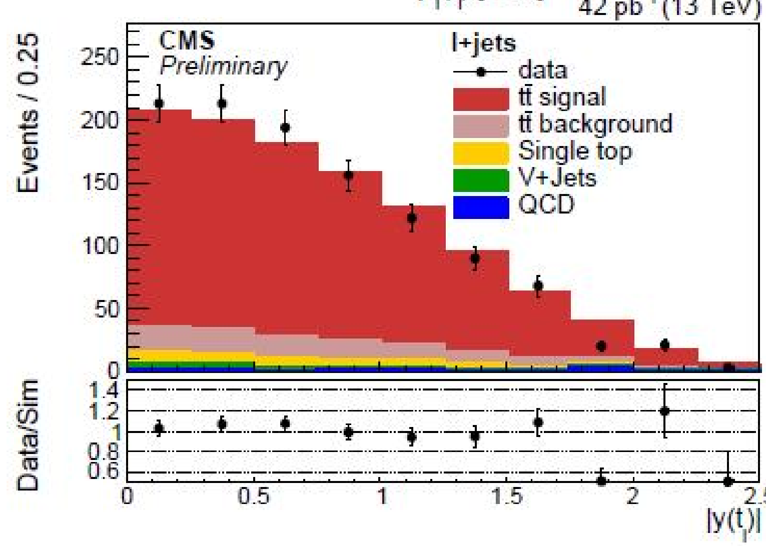
- Isolated e or μ with p_T>30 GeV
- ≥ 4 jets with p_T> 25 GeV (at least two above 35 GeV)
- ≥ 1 b-tag (working point 65% efficient with mistag rate of 3%)

Kinematic reconstruction of $t\bar{t}$ system

- For differential measurement→Otto's talk
- Cut on likelihood function (that includes mass constraints and neutrino momentum) to further reduce backgrounds
- Final sample is ~93% $t\bar{t}$ events

Backgrounds taken from MC

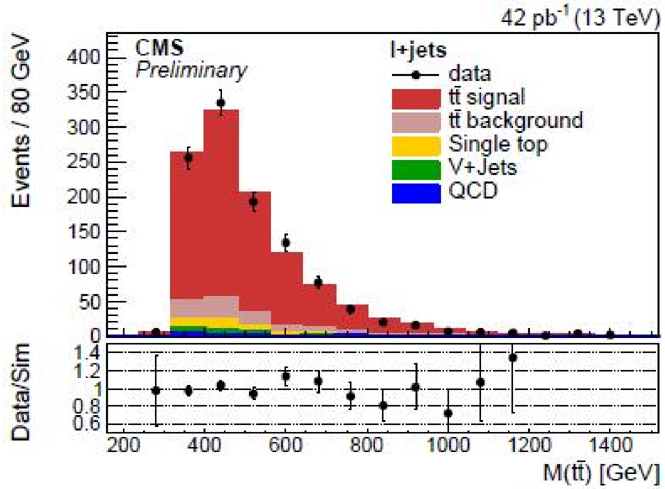


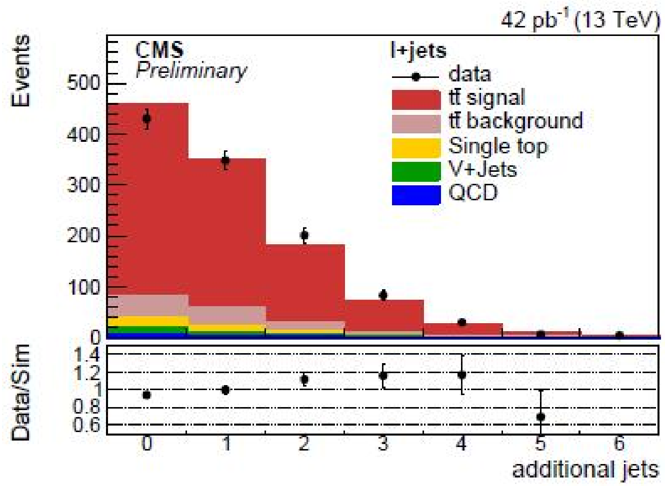


ℓ+jets Channel: Results

CMS-PAS-TOP-15-005

13 TeV
42 pb^{-1}





$$\sigma_{\text{tot}} = 836 \pm 27\,(\text{stat}) \pm 84\,(\text{sys}) \pm 100\,(\text{lumi})\ \text{pb}.$$

source	inclusive cross section [%]
statistical uncertainty	3.2
b tagging	5.1
jet energy scale	3.5
jet energy resolution	3.4
lepton selection	3.0
E_T^{miss} (non jet)	< 0.1
pileup	1.2
background	1.6
PDF	4.7
factorization scale	< 0.1
renormalization scale	< 0.1
NLO generator	2.0
POWHEG + PYTHIA8 vs. HERWIG++	3.4
total systematic uncertainty (no luminosity)	10.0
luminosity	12
total uncertainty	15.6

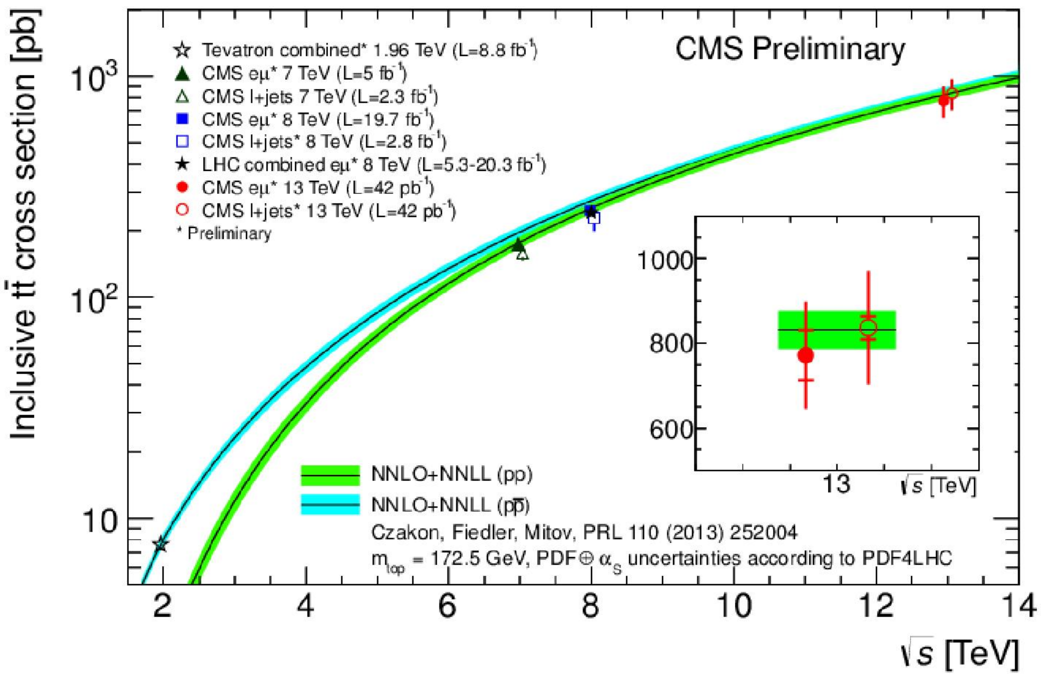
Conclusions

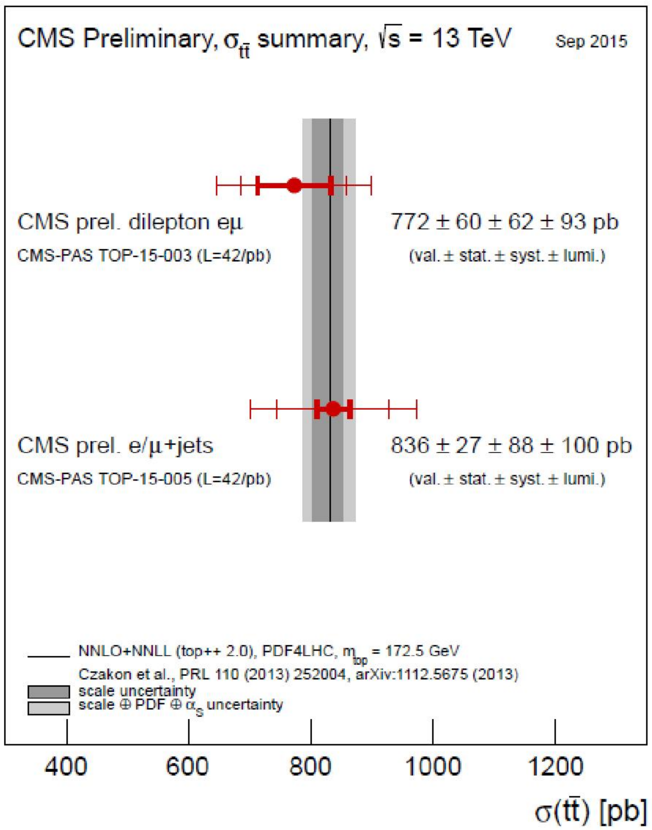
First 13 TeV results are now available!

- Both total and fiducial cross-sections have been measured

7 and 8 TeV datasets still providing additional measurements and precision.

New results forthcoming as RunII continues!





Thank you!

Bibliography

$\sqrt{s}$ (TeV)	luminosity	channel	Title
7	3.54 fb^{-1}	all-jets	Measurement of the $t\bar{t}$ production cross section in the all-jet final state in pp collisions at $\sqrt{s}=7$ TeV
8	18.4 fb^{-1}	all-jets	Measurement of the top quark pair production cross-section in the all-hadronic final state in pp collisions at $\sqrt{s}=8$ TeV
7	3.54 fb^{-1}	τ_h + jets	Measurement of the the $t\bar{t}$ production cross section in the τ + jets channel in pp collisions at $\sqrt{s}=7$ TeV
8	2.8 fb^{-1}	ℓ + jets	Top pair cross section in e/μ+jets at 8 TeV
13	42 pb^{-1}	ℓ + jets	Measurement of the inclusive and differential the $t\bar{t}$ production cross sections in lepton + jets final states at 13 TeV
8	19.6 fb^{-1}	τ_h + e or μ	Measurement of the $t\bar{t}$ production cross section in pp collisions at $\sqrt{s}=8$ TeV in dilepton final states containing one τ lepton
7+8	5+19.6 fb^{-1}	dilepton	Measurement of the the $t\bar{t}$ production cross section in the $e\mu$ channel in pp collisions at $\sqrt{s}=7$ and 8 TeV
13	42 pb^{-1}	dilepton	Measurement of the top quark pair production cross section in proton-proton collisions at $\sqrt{s}=13$ TeV with the CMS detector

Some Explanation for Some Systematic Uncertainties*

Trigger: estimated using tag-and-probe methods on Z events (single lepton) or using ${E_T}^{miss}$ or H_T cross-triggers (dilepton)

Lepton Identification/Isolation: estimated using tag-and-probe methods on Z events

Lepton Energy Scale: estimated by studying Z events in data and MC

Jet Energy Scale/Resolution and ${E_T}^{miss}$: estimated by varying the jet energies/${E_T}^{miss}$ by one standard deviation and recalculating ${E_T}^{miss}$ as needed

Pile-up: estimated by varying the inelastic cross-section or by varying the vertex reconstruction efficiencies in MC simulations

b-tagging: estimated by varying b-tagging scale factors within their statistical uncertainties

Backgrounds: for those taken from simulation, estimated by varying the normalizing cross-section. Uncertainties for data-driven estimates are method-dependent.

PDF: estimated by recalculating the acceptance after reweighting events using the NNPDF3.0 error sets (dilepton) or NNPDF30_nlo_as_0118 parameterization (single lepton)

Factorization/Renormalization: estimated by varying these scales up and down by a factor of two and reweighting the events

Generator/Hadronization Scheme: POWHEGv2 with Pythiav8.2 is used as nominal; MG5_AMC@NLO with Pythiav8.2 is used to compare generators, while POWHEGv2 with HERWIG++ is used to compare hadronization scheme

*PDF sets and generators listed here were used in the 13 TeV measurements. Earlier measurements use similar methods, but with the recommended information available at the time.

Full Systematic Tables

7 TeV $\tau_h + jets$

Source	Rel. uncert. [%]
W/Z/$t\bar{t}$ backgr. cross section uncert.	±3
Top-quark mass	±3
Renormalization/factorization scale	±2
Parton matching	±3
PDF	±5
τ_h trigger efficiency	±7
Pileup	+5 −1
τ_h energy scale	±7
τ_h identification	±9
Jet energy scale	±11
Jet energy resolution	±2
Unclustered E_T^{miss}	±7
b-tagging	±3
Multijet background reweighting	±5
Total syst. uncert.	±21
Stat. uncert. from fit and MC samples	±8
Stat. uncert. from trigger	±0.4
Total stat. uncert.	±8

8 TeV Lepton + τ_h

Source	Uncertainty [%]		
	$e\tau_h$	$\mu\tau_h$	Combined
Experimental uncertainties:			
τ_h jet identification	6.0	6.0	6.0
τ_h misidentification background	4.3	4.3	4.3
τ_h energy scale	2.4	2.5	2.5
b-jet tagging, jet misidentification	1.6	1.6	1.6
jet energy scale, jet energy resolution, E_T^{miss}	1.9	1.9	1.9
lepton reconstruction	0.8	0.6	0.5
other backgrounds	0.6	0.7	0.7
luminosity	2.6	2.6	2.6
Theoretical uncertainties:			
matrix element–parton shower matching	1.7	1.3	1.5
factorisation/renormalisation scale	2.9	2.9	2.9
generator	1.5	1.5	1.5
hadronisation	1.7	1.7	1.7
top-quark p_T modelling	0.7	0.5	0.6
parton distribution functions	0.8	0.7	0.7
total systematic uncertainty	9.6	9.5	9.5

Full Systematic Tables (cont.)

7+8 TeV dilepton

Source	Uncertainty [%]	
	7 TeV	8 TeV
Trigger	1.2	1.2
Lepton ID/isolation	1.4	1.5
Lepton energy scale	0.1	0.1
Jet energy scale	0.7	0.9
Jet energy resolution	0.1	0.1
Single top	0.9	0.6
DY	1.2	1.2
$t\bar{t}$ other	0.1	0.1
$t\bar{t}+V$	0.0	0.1
Diboson	0.2	0.6
W+jets	0.0	0.0
QCD	0.0	0.0
B-tag	0.5	0.5
Mistag	0.2	0.1
Pileup	0.3	0.3
Q^2 scale	0.3	0.3
ME/PS matching	0.2	0.1
MG+PY $\rightarrow$ PH+PY	0.2	0.4
Hadronization (JES)	0.6	0.8
Top p_T	0.3	0.3
Color reconnection	0.1	0.0
Underlying event	0.0	0.1
PDF	0.2	0.7
Luminosity	2.2	2.6
Statistical	1.2	0.6

CMS-PAS-TOP-14-018

All-Jets Channel

8 TeV
18.4 fb^{-1}