Latest Inclusive ttbar cross section results

Arun Nayak
Institute of Physics
Bhubaneswar, India
(For ATLAS & CMS Collaboration)

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Outline

- Introduction
- Cross section measurements
  - Dilepton channel
    - eμ, ee/μμ
  - Lepton + jets channel
  - Measurements of tt+bb, tt+V
  - All jets channel

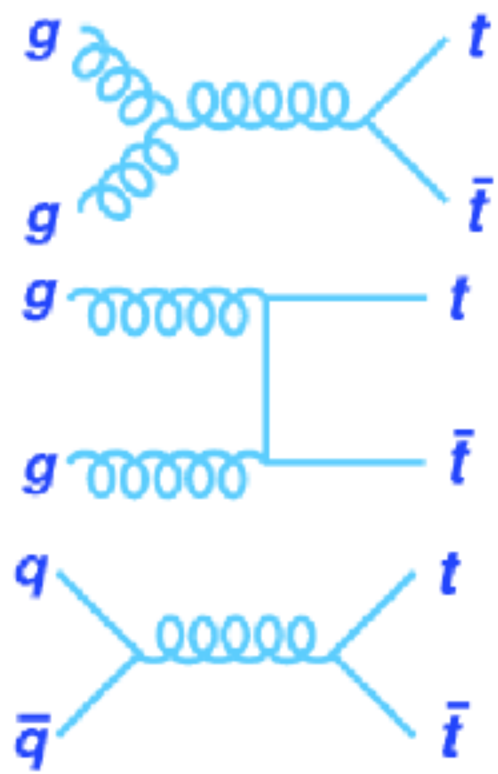
Latest measurements from 7, 8 and 13 TeV data are presented

Introduction

Measurement of the ttbar cross-section is important:

- Test of the SM QCD predictions
- Help constraining the PDFs, especially gluon
- Improve modeling and parameters in MC generator
- Main background to Higgs (in particular ttH) and many other new physics searches
- May also provide indirect evidence for BSM physics

Dominated by gluon fusion at LHC



NNLO+NNLL cross sections with m_t = 172.5 GeV

@ 7 TeV: 177.31 $^{+4.56}_{-5.99}$ (scale) ± 9.02 (PDF+α_s) $^{+5.44}_{-5.26}$ (mass)

@ 8 TeV: 252.89 $^{+6.39}_{-8.64}$ (scale) ± 11.67 (PDF+α_s) $^{+7.58}_{-7.33}$ (mass)

@ 13 TeV: 831.76 $^{+19.77}_{-29.2}$ (scale) ± 35.06 (PDF+α_s) $^{+23.18}_{-22.45}$ (mass)

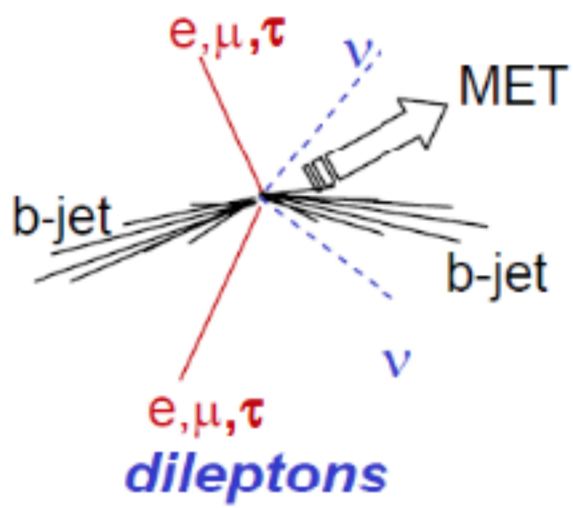
(using Top++v2.0 program)

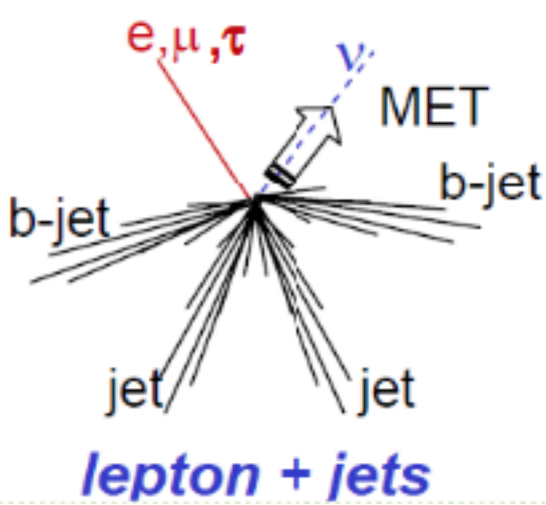
LHC Top X-Section working group
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCTopWG

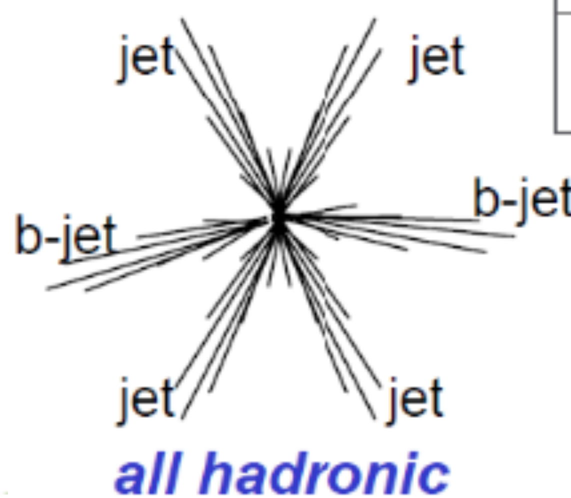
ttbar decay signatures

W decay defines the final state: Br(t→bW) = 100% in SM

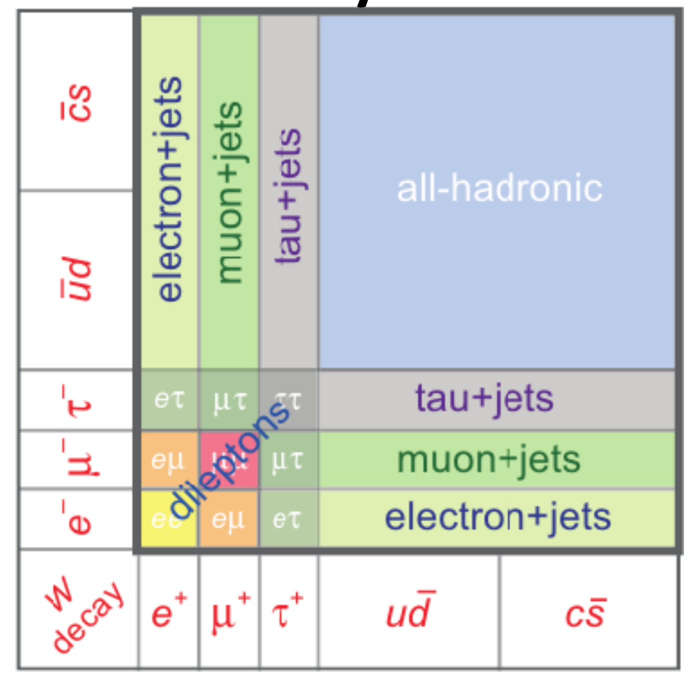
Focus on the latest measurements







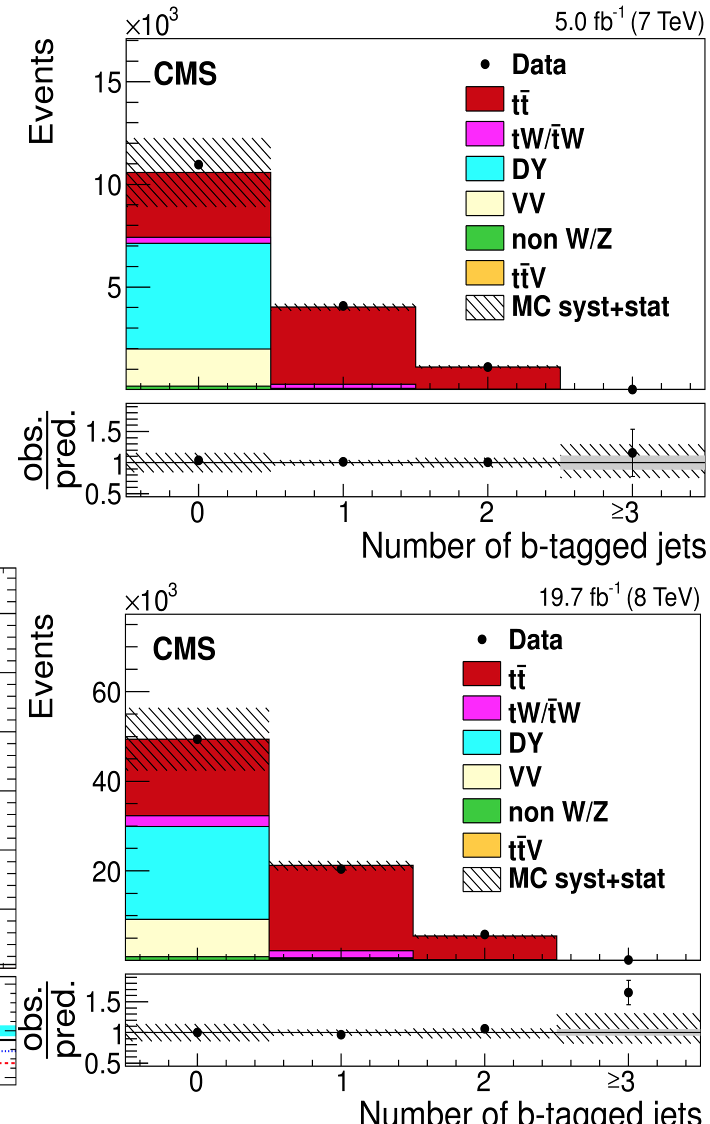
ttbar decay channels



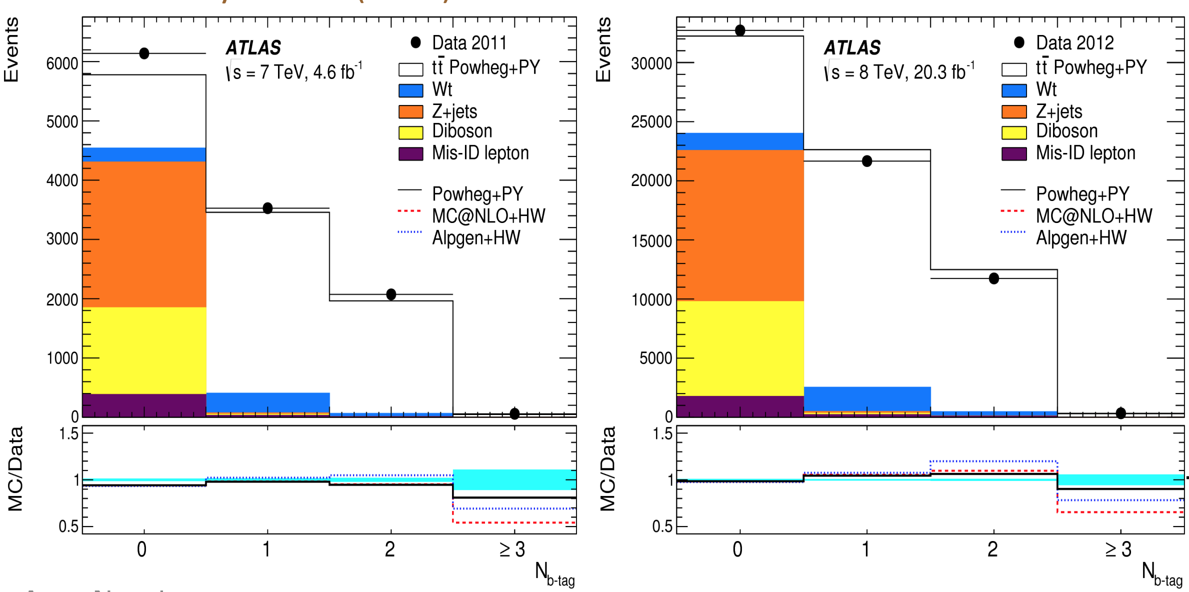
eμ + jets @ 7 & 8 TeV

CMS: JHEP 08 (2016) 029

- Small BR, but cleanest and most precise channel
- Event Selection:
  - Exactly 1e and 1μ, isolated, opposite sign
  - No minimum requirements on jets and b-tagged jets in CMS
    - Categories in N b-tagged jet and additional non-tagged N-jets
  - Requirement of 1 or 2 b-tagged jets in ATLAS



ATLAS: Eur.Phys.J. C74 (2014) 3109



eμ + jets @ 7 & 8 TeV

Eur.Phys.J. C74 (2014) 3109

ATLAS Measurement

Simultaneous measurement of ttbar x-section and b-tagging efficiency

$$N_1 = L\sigma_{t\bar{t}}\,\epsilon_{e\mu}2\epsilon_b(1 - C_b\epsilon_b) + N_1^{\text{bkg}}$$
$$N_2 = L\sigma_{t\bar{t}}\,\epsilon_{e\mu}C_b{\epsilon_b}^2 + N_2^{\text{bkg}}$$

- $\varepsilon_{e\mu}$: eμ selection efficiency
- ε_b: combined probability to reco and b-tag a jet within the fiducial volume
- $C_b = \varepsilon_{bb}/\varepsilon_b^2$: tagging correlation factor
  - represents change in tagging efficiency if one jet is already tagged

Background Estimation

Event counts	$\sqrt{s}=7$ TeV N_1	$\sqrt{s}=7$ TeV N_2	$\sqrt{s}=8$ TeV N_1	$\sqrt{s}=8$ TeV N_2
Data	3527	2073	21666	11739
Wt single top	326 ± 36	53 ± 14	2050 ± 210	360 ± 120
Dibosons	19 ± 5	0.5 ± 0.1	120 ± 30	3 ± 1
$Z(\to \tau\tau \to e\mu)$+jets	28 ± 2	1.8 ± 0.5	210 ± 5	7 ± 1
Misidentified leptons	27 ± 13	15 ± 8	210 ± 66	95 ± 29
Total background	400 ± 40	70 ± 16	2590 ± 230	460 ± 130

- Use SFs from Z→ee & Z→ μμ events to scale Z+HF events
- Fake leptons: Measured from data using SS leptons (OS/SS ratio from MC)

Inclusive cross-section:

7 TeV: $\boldsymbol{\sigma}_{tt}$ = 182.9 ± 3.1 (stat) ± 4.2 (syst) ± 3.6 (lumi) ± 3.3 (beam) pb

8 TeV: $\boldsymbol{\sigma}_{tt}$ = 242.4 ± 1.7 (stat) ± 5.5 (syst) ± 7.5 (lumi) ± 4.2 (beam) pb

$\boldsymbol{\varepsilon}_b$: 0.557 ± 0.009 (7 TeV) and 0.540 ± 0.006 (8 TeV) - consistent with simulation

eμ + jets @ 7 & 8 TeV

Eur.Phys.J. C74 (2014) 3109

ATLAS Measurement

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Fiducial cross-section: (Uncertainties: stat, syst, lumi, beam)

p_T^ℓ (GeV)	$\lvert\eta^\ell\rvert$	$W \to \tau \to \ell$	$\sqrt{s} = 7$ TeV (pb)	$\sqrt{s} = 8$ TeV (pb)
>25	<2.5	Yes	$2.615 \pm 0.044 \pm 0.056 \pm 0.052 \pm 0.047$	$3.448 \pm 0.025 \pm 0.069 \pm 0.107 \pm 0.059$
>25	<2.5	No	$2.305 \pm 0.039 \pm 0.049 \pm 0.046 \pm 0.041$	$3.036 \pm 0.022 \pm 0.061 \pm 0.094 \pm 0.052$
>30	<2.4	Yes	$2.029 \pm 0.034 \pm 0.043 \pm 0.040 \pm 0.036$	$2.662 \pm 0.019 \pm 0.054 \pm 0.083 \pm 0.046$
>30	<2.4	No	$1.817 \pm 0.031 \pm 0.039 \pm 0.036 \pm 0.033$	$2.380 \pm 0.017 \pm 0.048 \pm 0.074 \pm 0.041$

eμ + jets @ 7 & 8 TeV

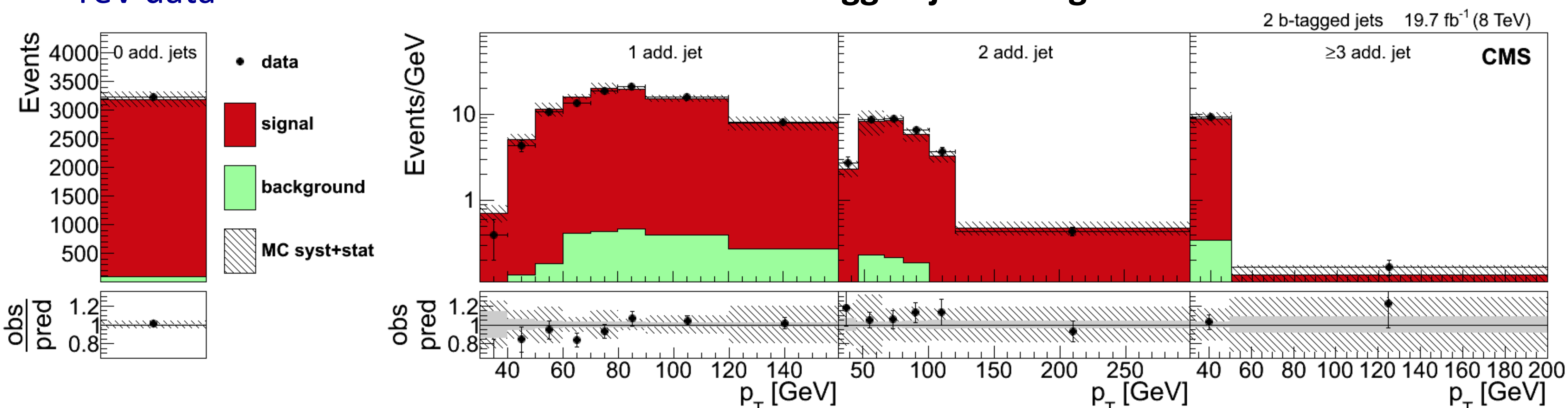
CMS Measurement

JHEP 08 (2016) 029

- Simultaneous 7 & 8 TeV binned likelihood fit
  - N b-tagged jet and additional non-tagged N-jets categories
  - Fit to the softest non-tagged jet p_T distribution in each category
- Major uncertainties: luminosity, trigger and lepton Id. efficiency etc..
- Uncertainties correlated between 7 & 8 TeV data

Source	Number of $e\mu$ events 7 TeV	Number of $e\mu$ events 8 TeV
DY	$22 \pm 3 \pm 3$	$173 \pm 25 \pm 26$
Non W/Z	$51 \pm 5 \pm 15$	$146 \pm 10 \pm 44$
Single top quark (tW)	$204 \pm 3 \pm 61$	$1034 \pm 3 \pm 314$
VV	$7 \pm 1 \pm 2$	$35 \pm 2 \pm 11$
$t\bar{t}V$	$12 \pm 1 \pm 3$	$84 \pm 1 \pm 26$
Total background	$296 \pm 6 \pm 63$	$1472 \pm 27 \pm 319$
$t\bar{t}$ dilepton signal	$5008 \pm 15 \pm 188$	$24440 \pm 44 \pm 956$
Data	4970	25441

2 b-tagged jets categories



eμ + jets @ 7 & 8 TeV

CMS Results

JHEP 08 (2016) 029

Fiducial Cross Section:

defined with events containing an eμ pair,
with $p_T > 20$ and $|\eta| < 2.4$.

$\sigma = 3.03 \pm 0.04(\text{stat}) \pm ^{0:08}_{0:07}(\text{syst}) \pm 0:07(\text{lumi})$ pb at 7 TeV (3.5%)
$\sigma = 4.23 \pm 0.02(\text{stat}) \pm ^{0:11}_{0:09}(\text{syst}) \pm 0:11(\text{lumi})$ pb at 8 TeV (3.6%)

Full Cross Section:

$\sigma = 173.6 \pm 2.1(\text{stat}) \pm ^{4.5}_{4.0}(\text{syst}) \pm 3.8(\text{lum})$ pb at 7 TeV (3.6%)
$\sigma = 244.9 \pm 1.4(\text{stat}) \pm ^{6.3}_{5.5}(\text{syst}) \pm 6.4(\text{lum})$ pb at 8 TeV (3.7%)

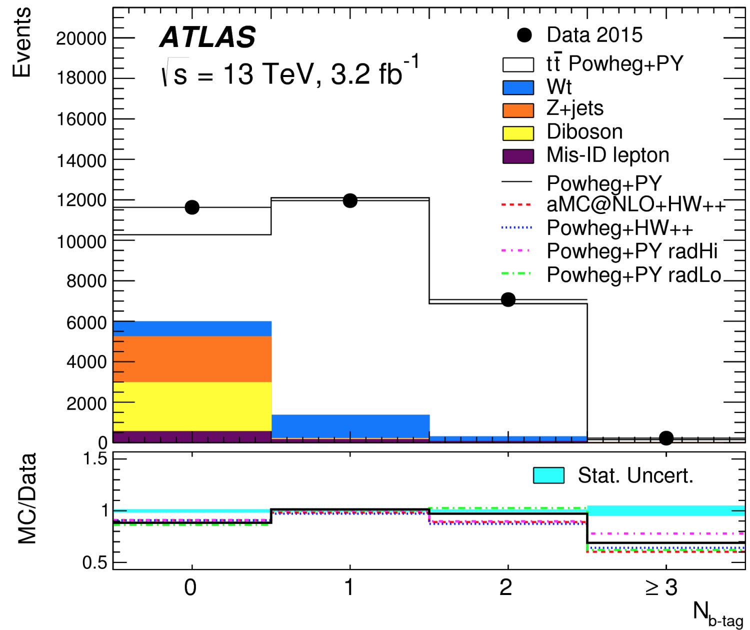
Ratio between 7 & 8 TeV results:
$R_{tt} = 1.41 \pm 0.06$ (in agreement with l+jets channel, later slides)

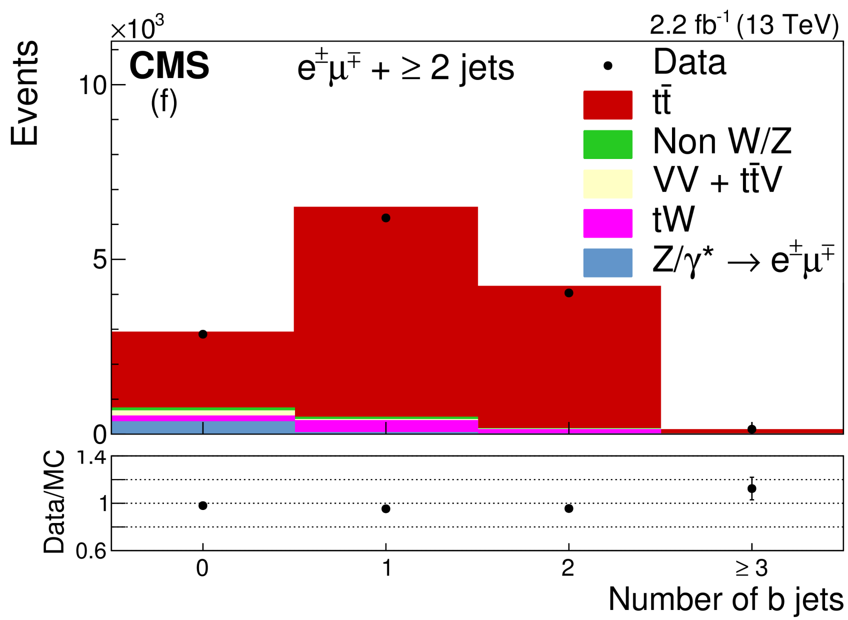
eμ + b-tagged jets @13 TeV

ATLAS:Phys. Lett. B761 (2016) 136, CMS:arXiv:1611.04040 (Submitted to Eur.Phys.J.C)

ATLAS:

- Similar strategy as the run-1 measurements
- Exactly one isolated, OS, eμ pair
- Count number of events in 1 or 2 b-tag bins
- Simultaneous measurement of x-section and b-tagging efficiency





CMS:

- Simple counting experiment
- Exactly one isolated, OS, eμ pair
- >= 2 jets
- >= 1 b-tagged jets

eμ + b-tagged jets @13 TeV

ATLAS:Phys. Lett. B761 (2016) 136 CMS:arXiv:1611.04040 (Submitted to Eur.Phys.J.C)

- Background estimation similar in both expts
- DY MC prediction normalized to Z-peak in data
- Fakes: Measured from data using SS leptons (OS/SS ratio from MC)
- tW, ttV and diboson from MC

Event Yield in ATLAS

Event counts	N_1	N_2
Data	11958	7069
Single top	1140 ± 100	221 ± 68
Diboson	34 ± 11	1 ± 0
$Z(\to \tau\tau \to e\mu)$+jets	37 ± 18	2 ± 1
Misidentified leptons	164 ± 65	116 ± 55
Total background	1370 ± 120	340 ± 88

Event Yield in CMS

Source	Number of $e^{\pm}\mu^{\mp}$ events
Drell–Yan	$46 \pm 5 \pm 7$
Non-W/Z leptons	$101 \pm 8 \pm 30$
Single top quark	$464 \pm 6 \pm 145$
VV	$15 \pm 2 \pm 5$
$t\bar{t}V$	$31 \pm 1 \pm 10$
Total background	$657 \pm 11 \pm 148$
$t\bar{t}$ signal	$10\,197 \pm 14 \pm 445$
Data	10368

ATLAS Results:

σ_{tt} = 818 ± 8 (stat) ± 27 (syst) ± 19 (lumi) ± 12 (beam) pb

ε_b = 0.559 ± 0.004 (stat) ± 0.003 (syst) - consistent with simulation (0.549)

σ_{tt}^{fid} = 11.32 ± 0.10 (stat) ± 0.29 (syst) ± 0.26 (lumi) ± 0.17 (beam) pb

CMS Result:

σ_{tt} = 792 ± 8(stat) ± 37(syst) ± 21(lumi) pb

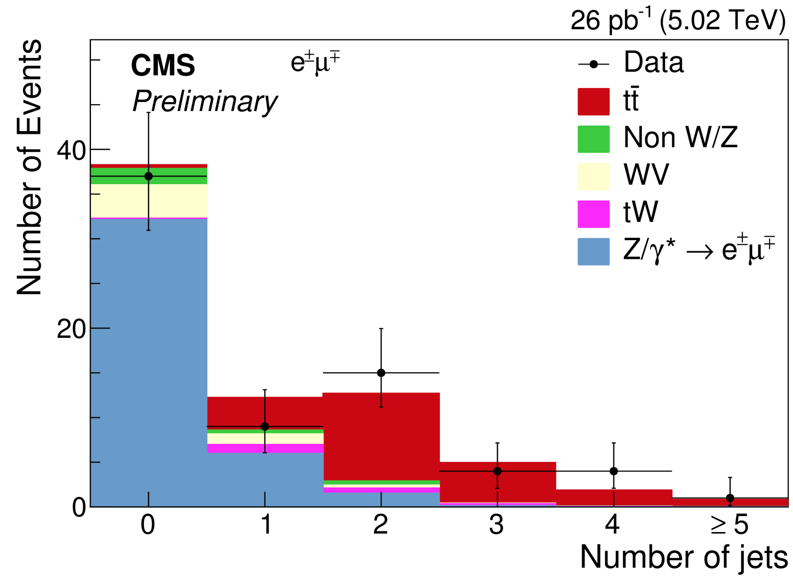
eμ + jets (5.02 TeV)

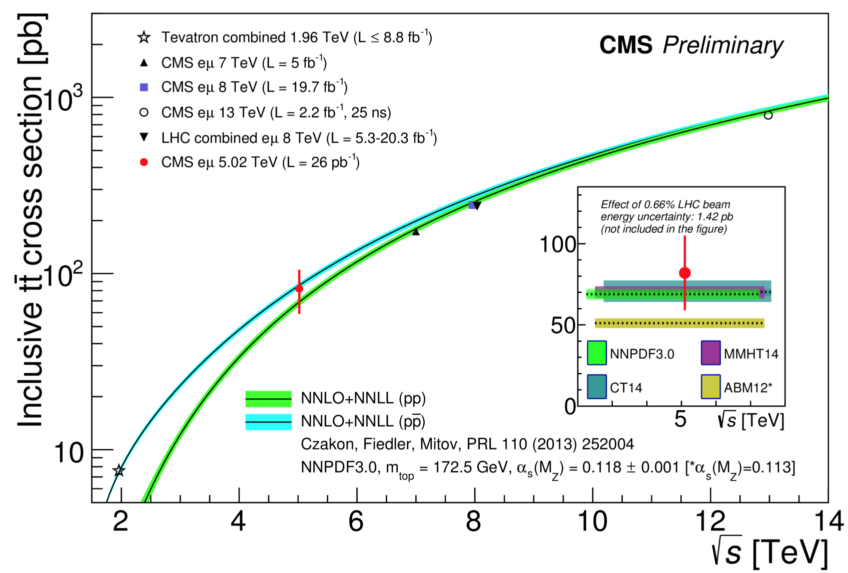
CMS-PAS-TOP-16-015

- Similar approach as measurement at 13 TeV
- >= 2 jets, No b-tagging requirements
- Dominated by statistical uncertainties (25%)

Source	Number of events $e^{\pm}\mu^{\mp}$ (stat. unc. only)
Drell–Yan	1.6 ± 0.4
Non W/Z	1.0 ± 0.9
t W	0.89 ± 0.02
WV	0.41 ± 0.02
Total background	3.9 ± 0.8
Signal ($t\bar{t} \to e\,\mu$)	17.0 ± 0.2
Data	24

σ_{tt} = 82 ± 20(stat) ± 5(syst) ± 10(lumi) pb

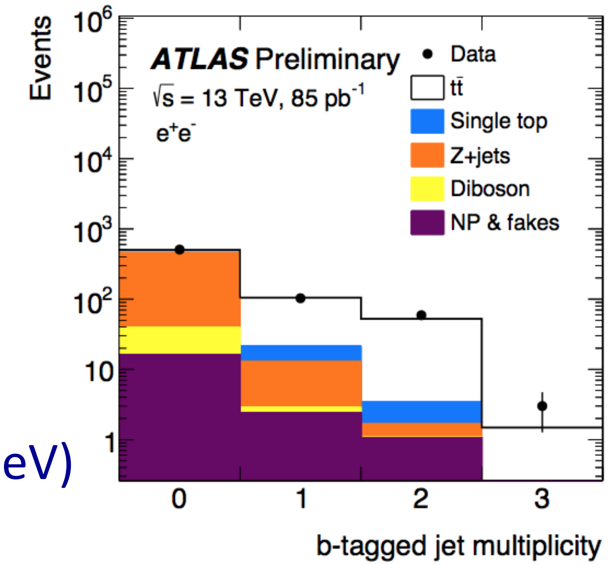




Dilepton: ee, μμ channel @ 13 TeV

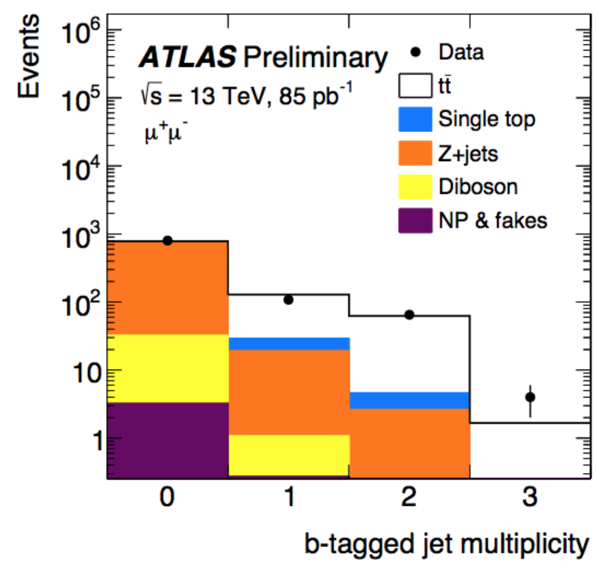
ATLAS-CONF-2015-049

- Measurement using 85 pb^{-1} of early Run 2 data
- Similar strategy as the eμ analysis
- Event Selection:
  - A pair of isolated, OS, same-flavour leptons
  - $E_T^{miss} > 30$ GeV
  - Veto events around Z mass window (+/- 10 GeV)



Extract σ_{tt} and b-tagging efficiencies simultaneously using a maximum likelihood fit

σ_{tt}(ee): 824 ± 88 (stat) ± 91 (syst) ± 82 (lumi) pb
σ_{tt}(μμ): 683 ± 74 (stat) ± 76 (syst) ± 68 (lumi) pb
σ_{tt}(ee+μμ): 749 ± 57 (stat) ± 79 (syst) ± 74 (lumi) pb



ℓ+jets @ 8 TeV

ATLAS Analysis

Phys. Rev. D 91, 112013 (2015)

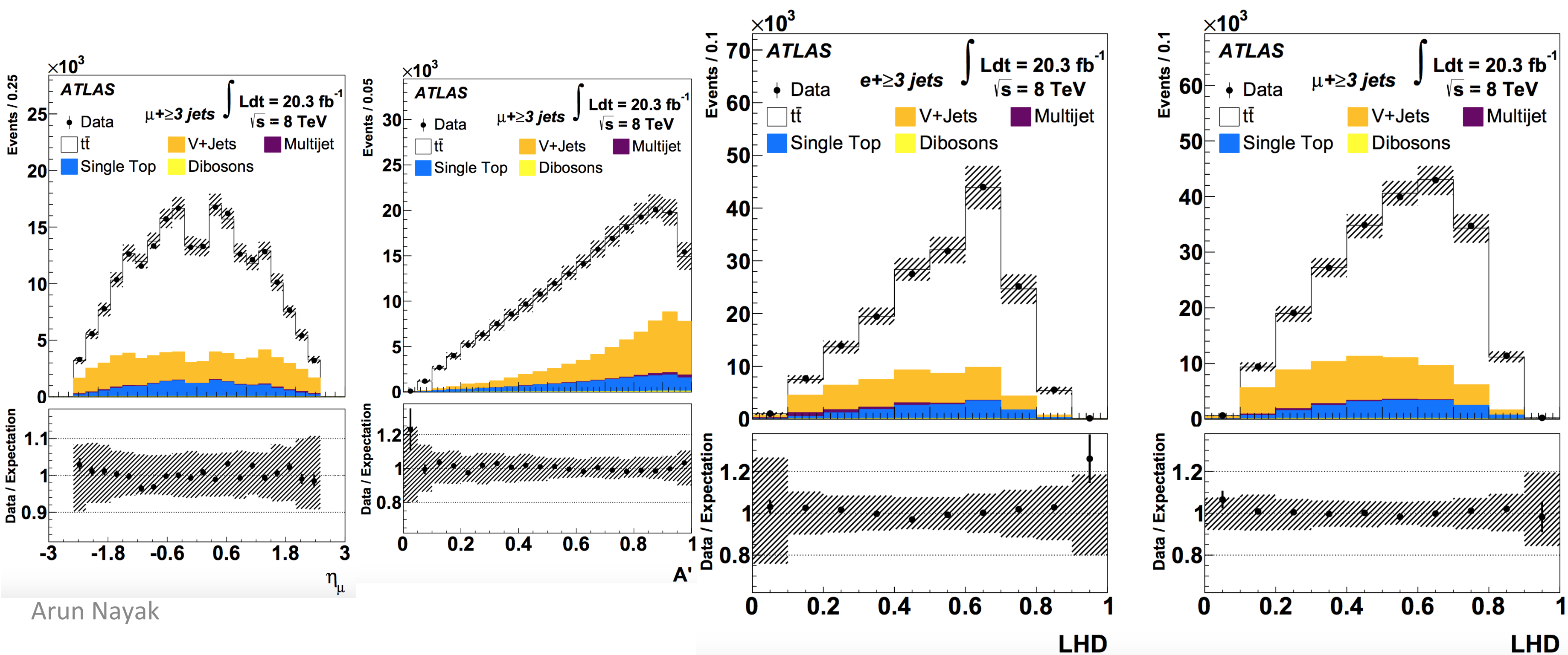
Event Selection

- e/μ + ≥ 3 jets; ≥ 1 b-tagged jet
- E_T^{miss} > 30 GeV
- m_T^W > 30 GeV

Analysis Strategy:

Determine the number of events using a template fit to a likelihood discriminant, constructed as product of PDFs of two kinematic variables:

Lepton η, Transformed Aplanarity



ℓ+jets @ 8 TeV

ATLAS Results

Phys. Rev. D 91, 112013 (2015)

Measured Inclusive x-sections:

$$e\text{+jets} : \sigma_{t\bar{t}} = 256 \pm 2(\text{stat.}) \ \pm 25(\text{syst.}) \ \pm 7(\text{lumi.}) \ \pm 4(\text{beam}) \text{ pb},$$

$$\mu\text{+jets} : \sigma_{t\bar{t}} = 260 \pm 1(\text{stat.}) \ {}^{+22}_{-23}(\text{syst.}) \ \pm 8(\text{lumi.}) \ \pm 4(\text{beam}) \text{ pb},$$

$$\ell\text{+jets} : \sigma_{t\bar{t}} = 258 \pm 1(\text{stat.}) \ {}^{+22}_{-23}(\text{syst.}) \ \pm 8(\text{lumi.}) \ \pm 4(\text{beam}) \text{ pb},$$

Measured Fiducial x-sections:

$$e\text{+jets} : \sigma^{\text{fid}}_{t\bar{t}} = 11.3 \pm 0.1(\text{stat.}) \ \pm 1.0(\text{syst.}) \ \pm 0.3(\text{lumi.}) \ \pm 0.2(\text{beam}) \text{ pb},$$

$$\mu\text{+jets} : \sigma^{\text{fid}}_{t\bar{t}} = 11.5 \pm 0.1(\text{stat.}) \ \pm 1.0(\text{syst.}) \ \pm 0.3(\text{lumi.}) \ \pm 0.2(\text{beam}) \text{ pb},$$

$$\ell\text{+jets} : \sigma^{\text{fid}}_{t\bar{t}} = 22.8 \pm 0.1(\text{stat.}) \ {}^{+1.9}_{-2.0}(\text{syst.}) \ \pm 0.7(\text{lumi.}) \ \pm 0.4(\text{beam}) \text{ pb},$$

ℓ+jets @ 7 & 8 TeV

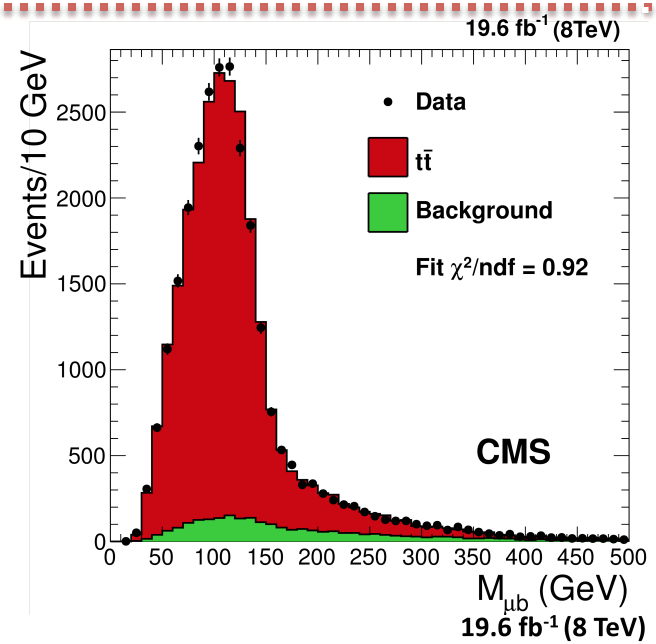
arXiv:1602.09024

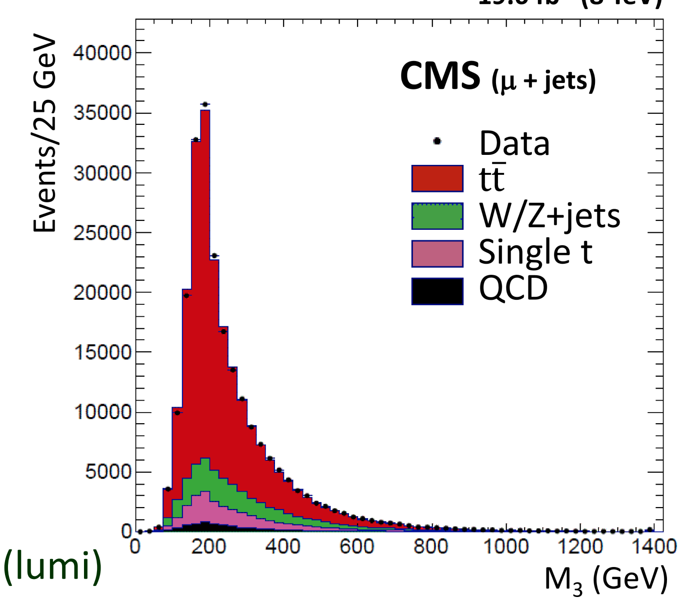
CMS Analysis Strategy:

- 1 isolated high-p_T e/μ, ≥ 4 jets, ≥ 1 b-tagged jet
- Fit to M_{lb}
- Cross check: fit to M_3 (three-jet combination with the highest p_T)
- e/μ+jets channels combined using the BLUE method
- QCD background shape from data
- Major syst: JES, modeling, Q^2 scale

Analysis	Generator	Channel	$\sigma_{t\bar{t}}$ at $\sqrt{s} = 8$ TeV
$M_{\ell b}$	MADGRAPH	μ+jets	$228.9 \pm 3.4 \pm 13.7 \pm 6.0$ pb
		e+jets	$234.6 \pm 3.9 \pm 15.2 \pm 6.2$ pb
		Combined	$228.5 \pm 3.8 \pm 13.7 \pm 6.0$ pb
$M_{\ell b}$	POWHEG	Combined	$237.1 \pm 3.9 \pm 14.2 \pm 6.2$ pb
M_3	MADGRAPH	μ+jets	$228.7 \pm 2.6 \pm 19.0 \pm 6.0$ pb
		e+jets	$225.8 \pm 2.4 \pm 19.1 \pm 5.9$ pb
		Combined	$227.1 \pm 2.5 \pm 19.1 \pm 6.0$ pb
M_3	POWHEG	Combined	$238.4 \pm 2.8 \pm 20.0 \pm 6.2$ pb

Analysis	Generator	Channel	$\sigma_{t\bar{t}}$ at $\sqrt{s} = 7$ TeV
$M_{\ell b}$	MADGRAPH	μ+jets	$157.7 \pm 5.5 \pm 13.2 \pm 3.4$ pb
		e+jets	$165.8 \pm 6.5 \pm 12.8 \pm 3.6$ pb
		Combined	$161.7 \pm 6.0 \pm 12.0 \pm 3.6$ pb





8TeV / 7 TeV : 1.43 ± 0.04 (stat) ± 0.07 (syst) ± 0.05 (lumi)

ℓ+jets @ 13 TeV

ATLAS-CONF-2015-049

ATLAS Analysis:

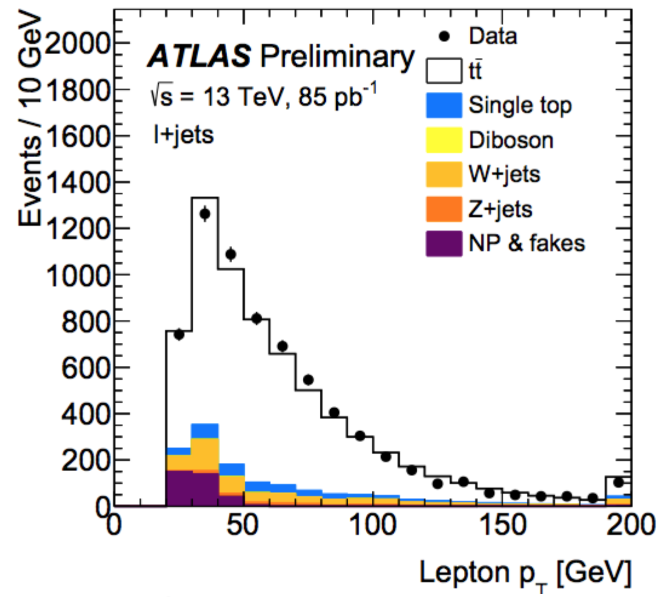
Results with 85 pb^{-1} of early Run 2 data

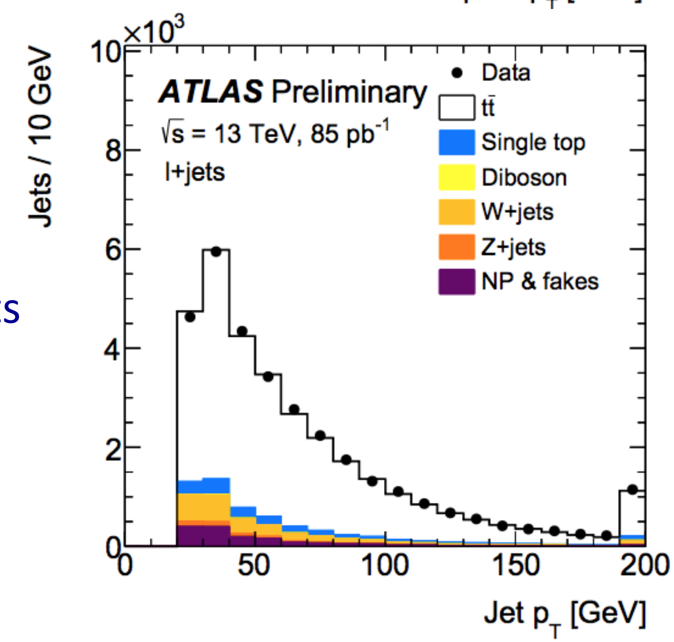
Event selection

- 1 e or μ
- ≥ 4 jets, ≥ 1 b-tagged jets
- e+jets: $E_T^{miss} > 40$ GeV or $m_T^W > 50$ GeV
- μ+jets: $E_T^{miss} + m_T^W > 60$ GeV

Cross section measured using simple counting events

$$\sigma_{tt} = 817 \pm 13\,(\text{stat}) \pm 103\,(\text{syst}) \pm 88\,(\text{lumi})\ \text{pb}$$



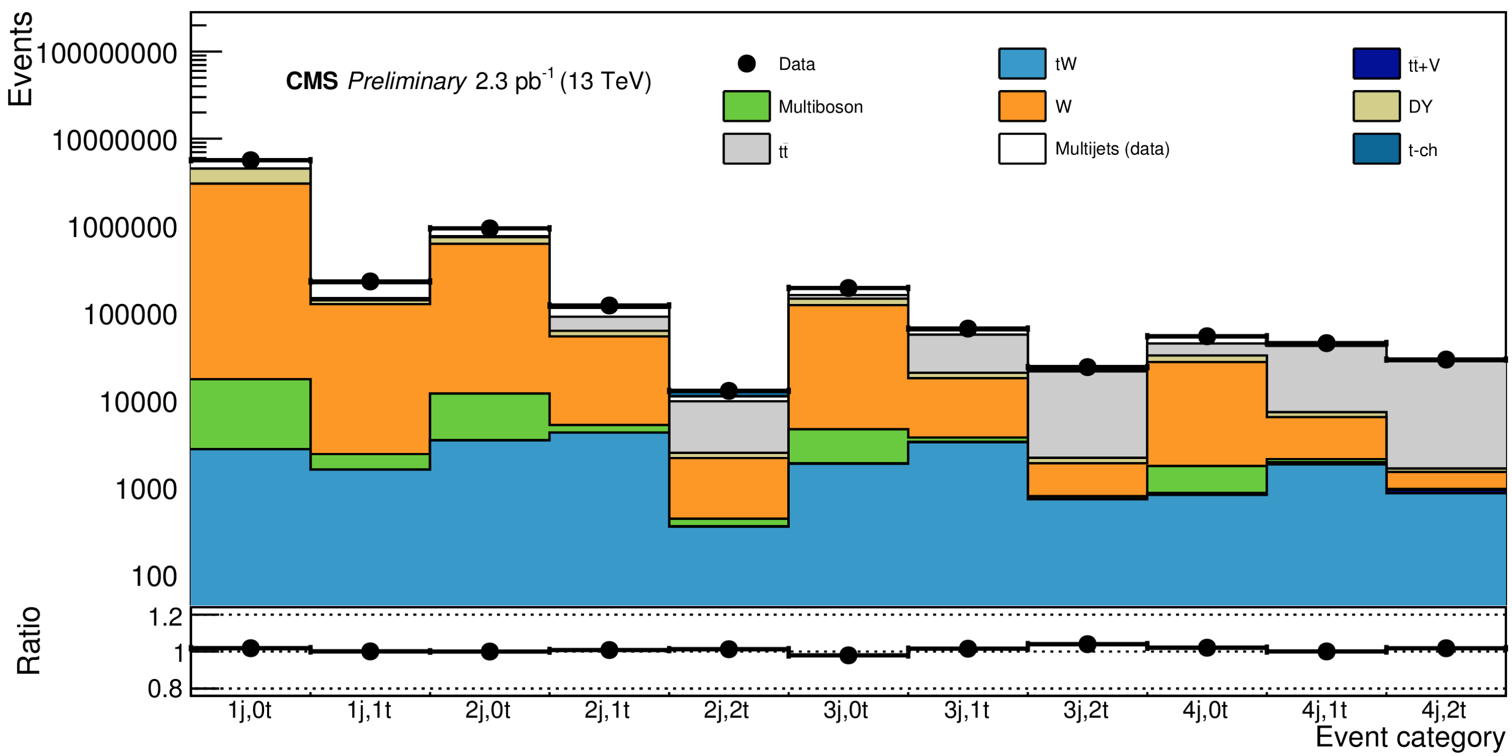


ℓ+jets @ 13 TeV

CMS-PAS-TOP-16-006

CMS Analysis Strategy

- Analysis with 2015 data
- Select events with only 1 lepton and at least 1 jet
- Categorize events based on number of jets and b-tagged jets
- Low jet/b-tag categories are used to constrain backgrounds while high jet/b-tag are fitted to extract the signal
- QCD background estimated from data



ℓ+jets @ 13 TeV

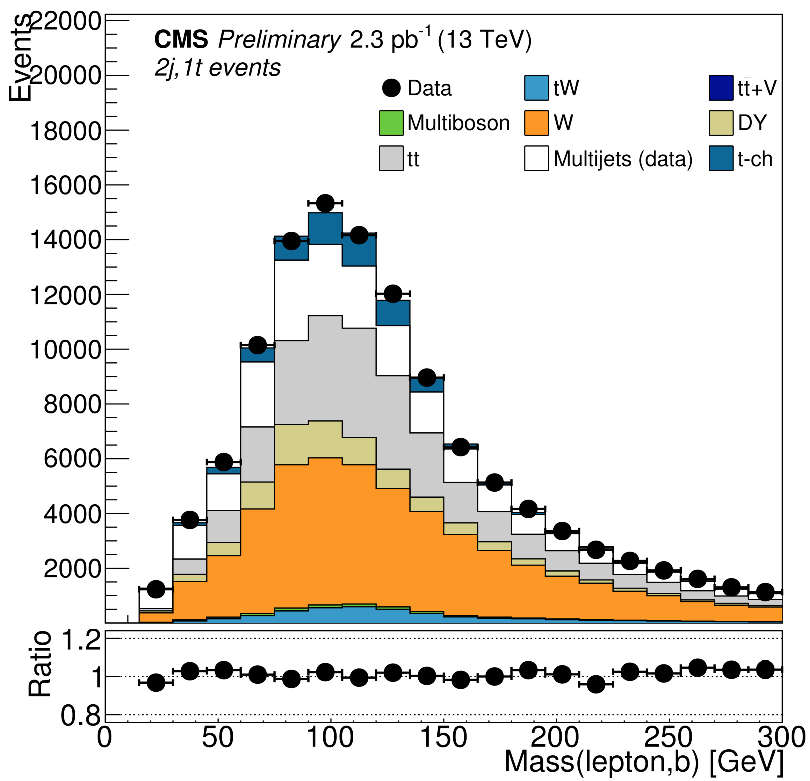
CMS Results

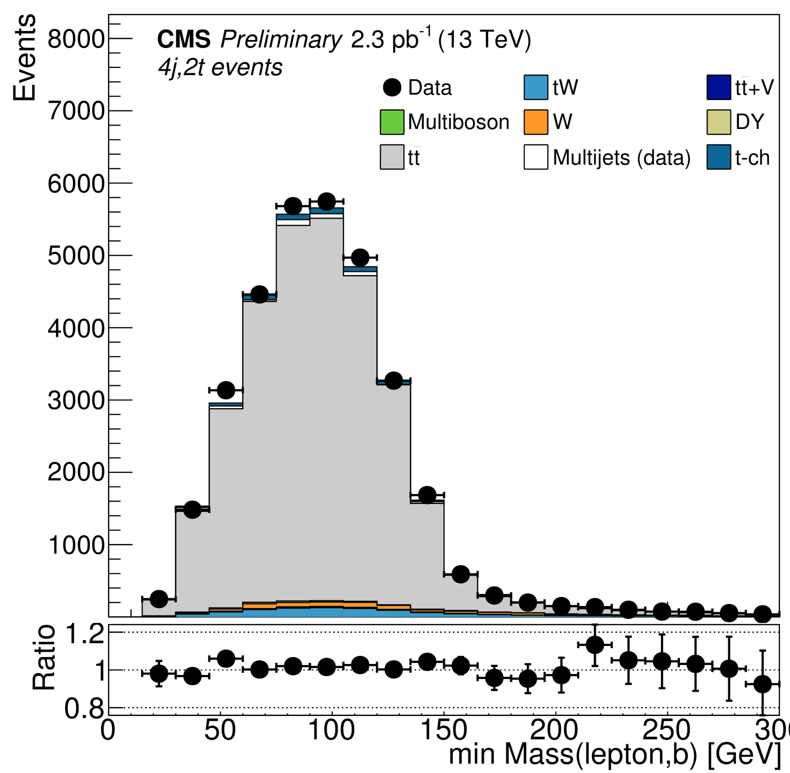
CMS-PAS-TOP-16-006

Simultaneous binned likelihood fit

- Fit to M_{lb} or min(M_{lb})
- Shape fit to all categories

$$\sigma_{tt} = 834.6 \pm 2.5(\textbf{stat}) \pm 22.8(\textbf{syst}) \pm 22.5(\textbf{lumi})$$

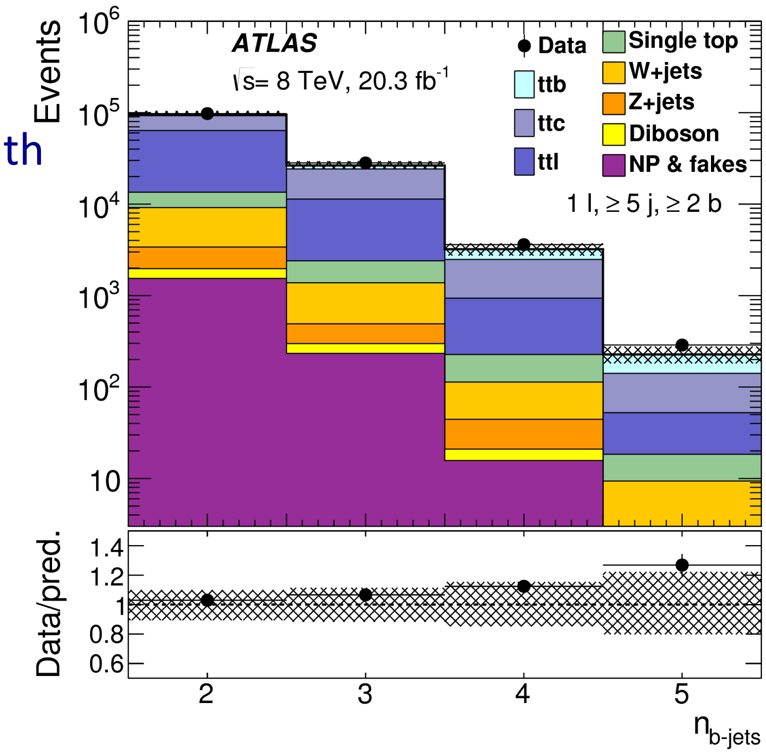




tt+bb @ 8 TeV

ATLAS: EPJC (2016)76:11

- Comparison with NLO QCD calculations
- Irreducible bkg. for tt +H(bb)
- Measurements for fiducial cross section of ttbar with 1 or 2 b-tagged jets
- Measure ratio (tt+bb)/(tt+jj): Cancellation of uncertainties
- Event Selection:
  - Both dilepton and lepton+jets channels
  - Signal extraction by fit to the b-tagging MVA discriminant
  - A cross checked cut-based analysis with very tight criteria for tt+2b measurement

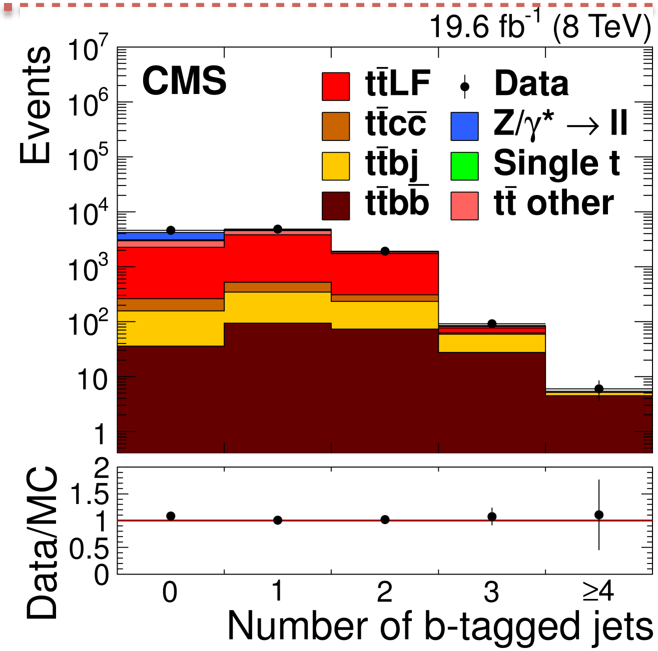


	ttbb [fb]	*ttb* Lepton-plus-jets [fb]	*ttb eμ* [fb]	R_{ttbb} (%)
Observed	(cut-based) 18.2 ±3.5 ±5.7 (fit-based) 12.4 ±3.3 ±3.6	$930 \pm 70 ^{+240}_{-190}$	$48 \pm 10 ^{+15}_{-10}$	1.20 ±0.33 ±0.28

tt+bb @ 8 TeV

CMS: PLB 746 (2015) 132

- Comparison with NLO QCD calculations
- Irreducible bkg. for tt +H(bb)
- Measure ratio (tt+bb)/(tt+jj): large cancellation of uncertainties
  - Selection: dilepton events with 4 jets with p_T > 30 GeV, 2 b-tagged jets
  - Signal extraction by fit to the measured b-tagging algorithm discriminators
  - Corrected to particle level
  - Dominant syst. unc.: b-efficiency, mistag rate etc..



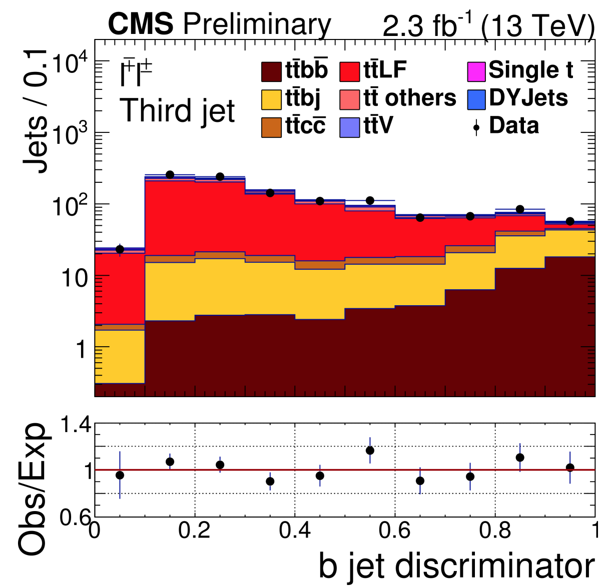
Phase Space (PS)	$\sigma_{t\bar{t}b\bar{b}}$ [pb]	$\sigma_{t\bar{t}jj}$ [pb]	$\sigma_{t\bar{t}b\bar{b}}/\sigma_{t\bar{t}jj}$
Visible PS (particle)			
Jet $p_T > 20\,\mathrm{GeV}/c$	$0.029 \pm 0.003 \pm 0.008$	$1.28 \pm 0.03 \pm 0.15$	$0.022 \pm 0.003 \pm 0.005$
Full PS (parton)			
Jet $p_T > 20\,\mathrm{GeV}/c$	$1.11 \pm 0.11 \pm 0.31$	$52.1 \pm 1.0 \pm 6.8$	$0.021 \pm 0.003 \pm 0.005$
Jet $p_T > 40\,\mathrm{GeV}/c$	$0.36 \pm 0.08 \pm 0.10$	$16.1 \pm 0.7 \pm 2.1$	$0.022 \pm 0.004 \pm 0.005$
NLO calculation			
Jet $p_T > 40\,\mathrm{GeV}/c$	0.23 ± 0.05	21.0 ± 2.9	0.011 ± 0.003

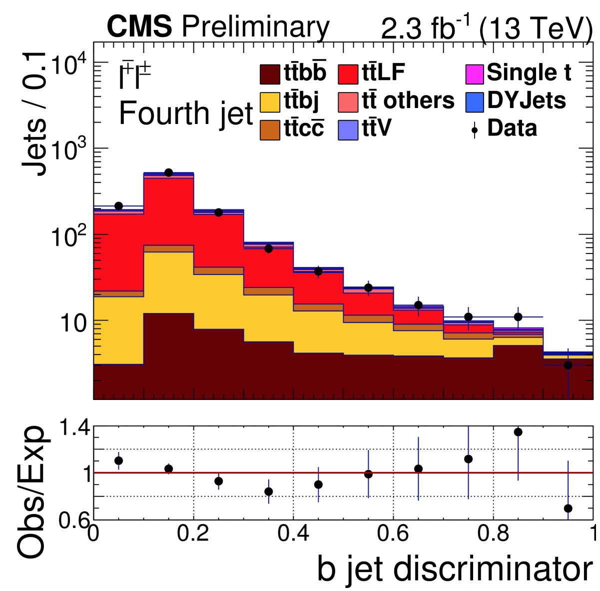
tt+bb @ 13 TeV

CMS-PAS-TOP-16-010

Similar to run-1 analysis

- Comparison with NLO QCD calculations
- Irreducible bkg. for tt +H(bb)
- Measure ratio (tt+bb)/(tt+jj): large cancellation of uncertainties
  - Selection: dilepton events with 4 jets with p_T > 30 GeV, 2 b-tagged jets
  - Signal extraction by fit to the measured b-tagging algorithm discriminators
  - Corrected to particle level
  - Dominant syst. unc.: b-efficiency, mistag rate etc..





Phase Space	$\sigma_{t\bar{t}b\bar{b}}$ [pb]	$\sigma_{t\bar{t}jj}$ [pb]	$\sigma_{t\bar{t}b\bar{b}} / \sigma_{t\bar{t}jj}$
Measurement			
Visible	$0.085 \pm 0.012 \pm 0.029$	$3.5 \pm 0.1 \pm 0.7$	$0.024 \pm 0.003 \pm 0.007$
Full	$3.9 \pm 0.6 \pm 1.3$	$176 \pm 5 \pm 33$	$0.022 \pm 0.003 \pm 0.006$
Simulation (POWHEG)			
Visible	0.070 ± 0.009	5.1 ± 0.5	0.014 ± 0.001
Full	3.2 ± 0.4	257 ± 26	0.012 ± 0.001

σ_{tt}/σ_Z @ 13 TeV

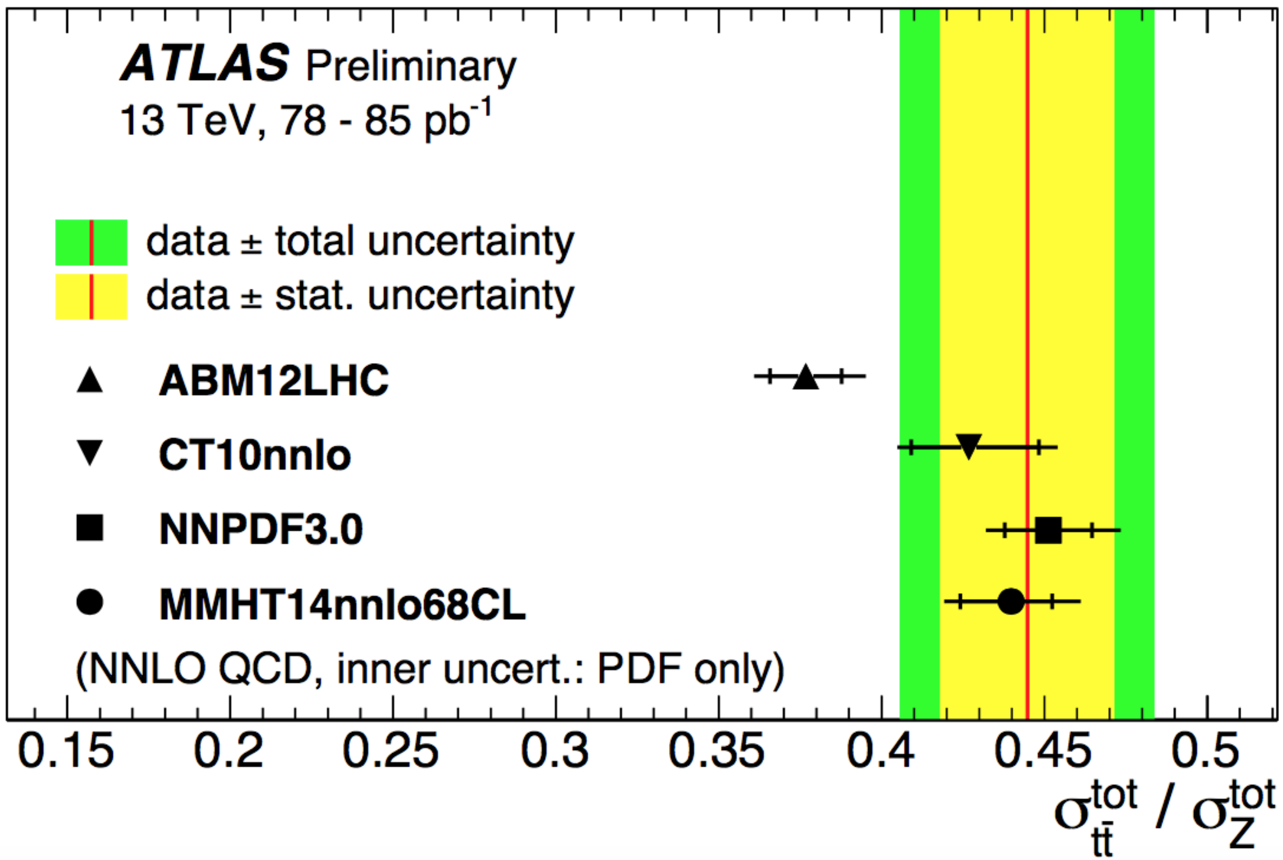
ATLAS-CONF-2015-049

The ratio is defined as: $$R_{t\bar{t}/Z} = \frac{\sigma_{t\bar{t}}}{0.5\left(\sigma_{Z\to ee} + \sigma_{Z\to\mu\mu}\right)}$$

Cancellation of systematics: e.g. lumi and lepton related uncertainties

Measurement using 78 pb^{-1} for σ_{tt} and 85 pb^{-1} for σ_Z

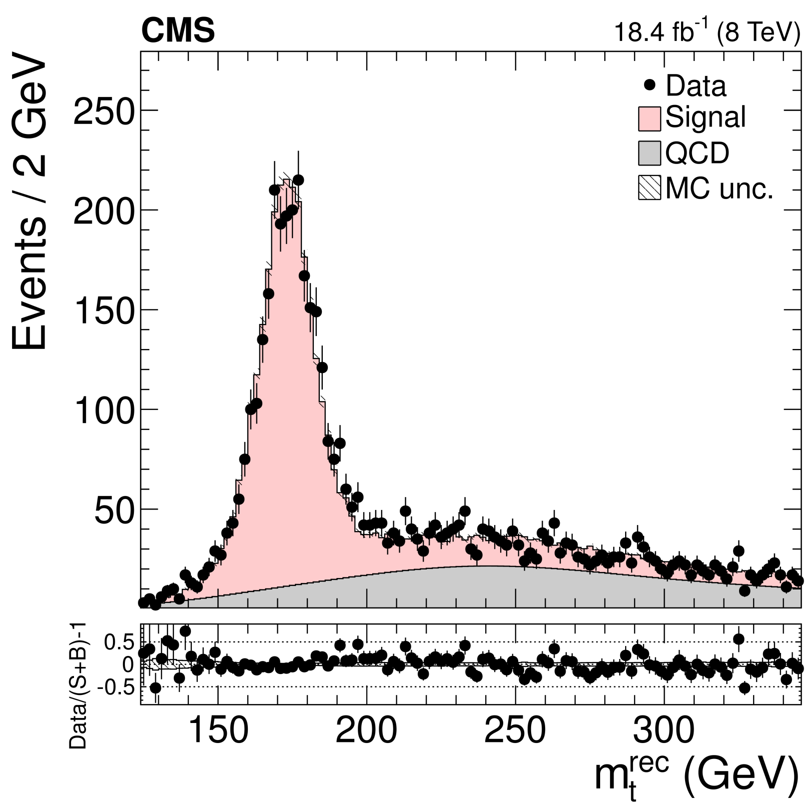
σ_{tt}/σ_Z = 0.445 ± 0.027 (stat) ± 0.028 (syst)

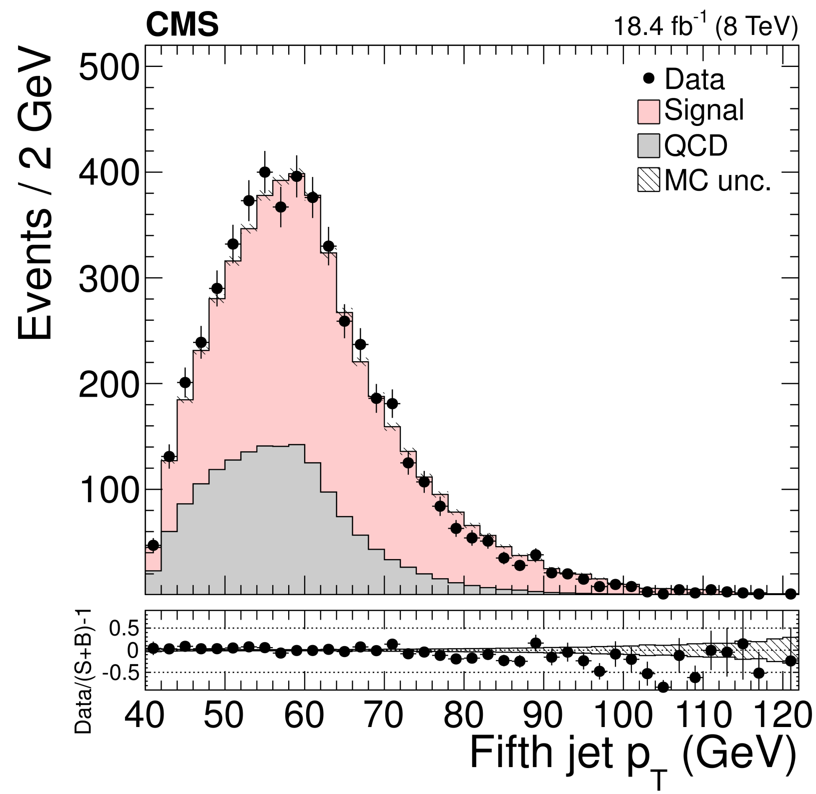


All jets @ 8 TeV

CMS Results
Eur. Phys. J. C 76 (2016) 128

- Large BR (~46%), very large bkg. (QCD multijet)
- Events selected using multijet trigger
- Signature: ≥ 6 jets, ≥ 2 b-tagged jets





- Reconstruction of ttbar system
- Unbinned maximum likelihood fit to m_t to extract signal and background normalizations

σ_{tt} = 275.6 ± 6.1(stat) ± 37.8(syst) ± 7.2(lumi) pb

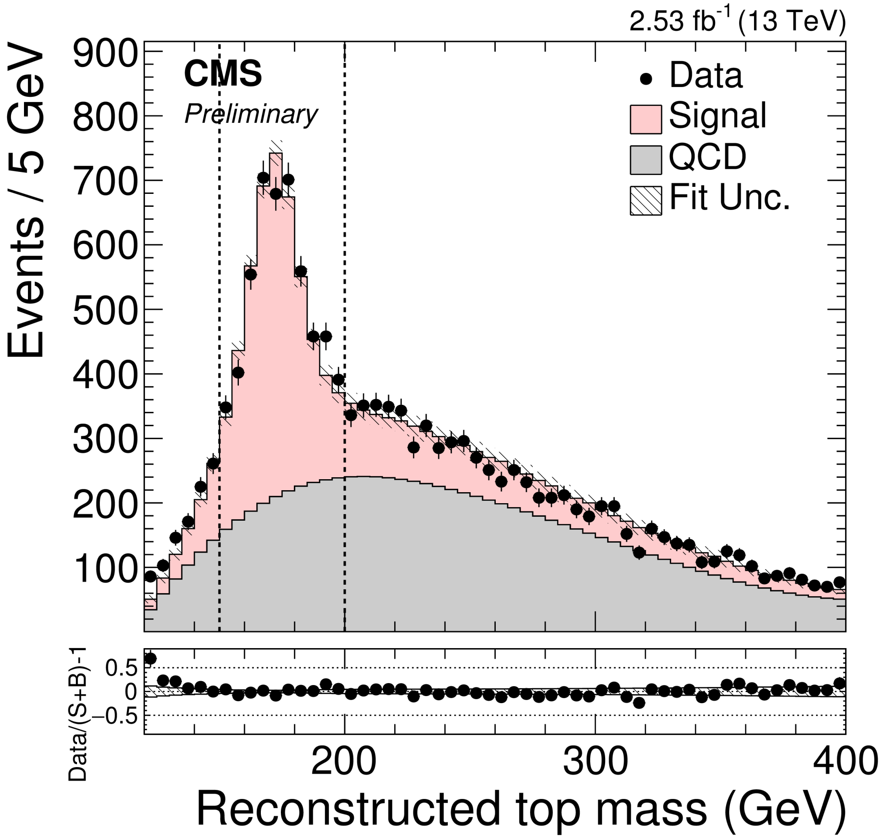
All jets @ 13 TeV

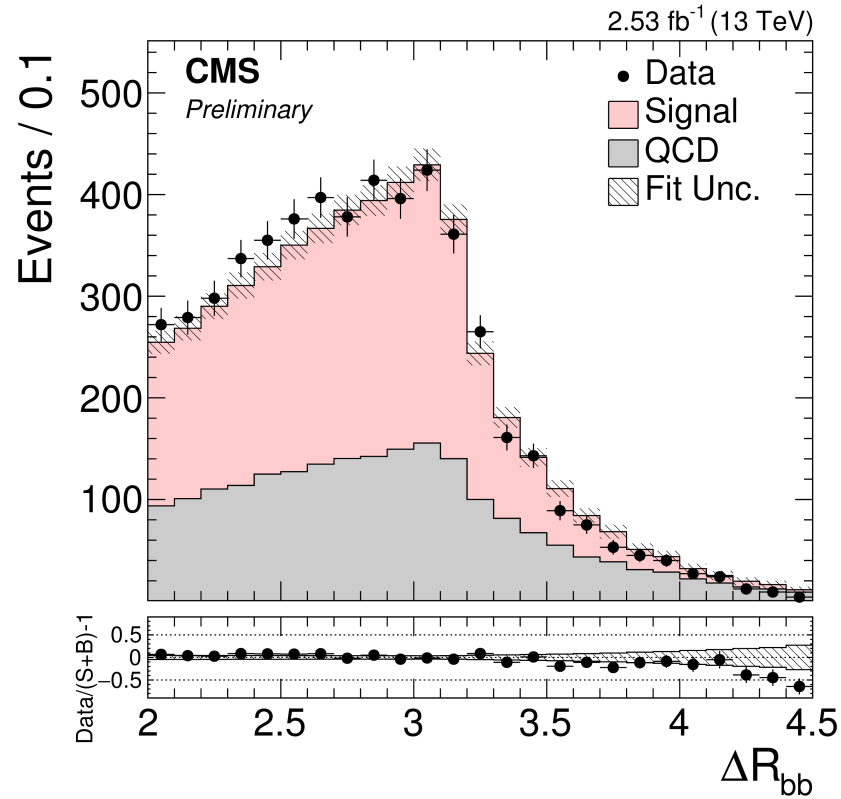
CMS Results

CMS-PAS-TOP-16-013

Similar strategy as 8 TeV:

Unbinned maximum likelihood fit to m_t





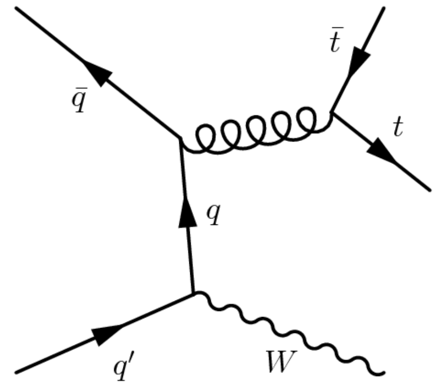
$\sigma_{tt} = 834 \pm 25(\text{stat})\ ^{+118}_{-104}(\text{syst}) \pm 23(\text{lumi})$ pb

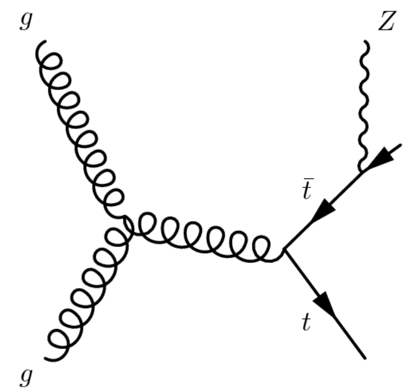
Measurement also performed in boosted regime:

$\sigma_{tt} = 727 \pm 46(\text{stat})\ ^{+115}_{-112}(\text{syst}) \pm 8(\text{lumi})$ pb

ttW & ttZ

- The cross section can be altered due to presence of new physics beyond SM
- Final states with either two or more leptons
- Further categories to enhance signal
- Inclusive cross sections are extracted using likelihood fits to signal and control regions





ATLAS Channels @ 8 TeV

Process	$t\bar{t}$ decay	Boson decay	Channel	$Z \to \ell^+\ell^-$
$t\bar{t}W^\pm$	$(\ell^\pm\nu b)(q\bar{q}b)$	$\ell^\mp\nu$	OS dilepton	no
	$(\ell^\pm\nu b)(\ell^\mp\nu b)$	$q\bar{q}$	OS dilepton	no
	$(\ell^\pm\nu b)(q\bar{q}b)$	$\ell^\pm\nu$	SS dilepton	no
	$(\ell^\pm\nu b)(\ell^\mp\nu b)$	$\ell^\pm\nu$	Trilepton	no
$t\bar{t}Z$	$(\ell^\pm\nu b)(\ell^\mp\nu b)$	$q\bar{q}$	OS dilepton	no
	$(q\bar{q}b)(q\bar{q}b)$	$\ell^+\ell^-$	OS dilepton	yes
	$(\ell^\pm\nu b)(q\bar{q}b)$	$\ell^+\ell^-$	Trilepton	yes
	$(\ell^\pm\nu b)(\ell^\mp\nu b)$	$\ell^+\ell^-$	Tetralepton	yes

CMS Channels @ 8 & 13 TeV

ttW : SS dilepton

ttZ : Trilepton, Tetralepton

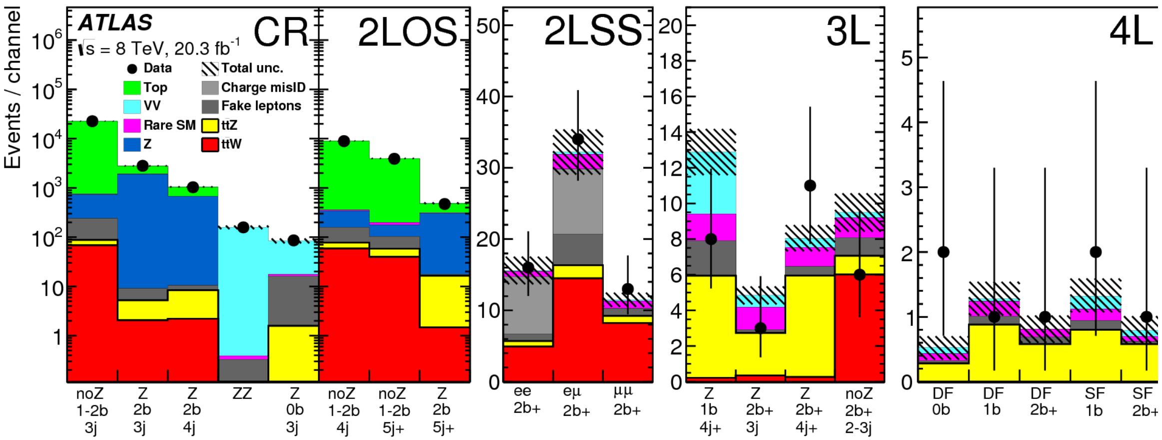
ATLAS Channels @ 13 TeV

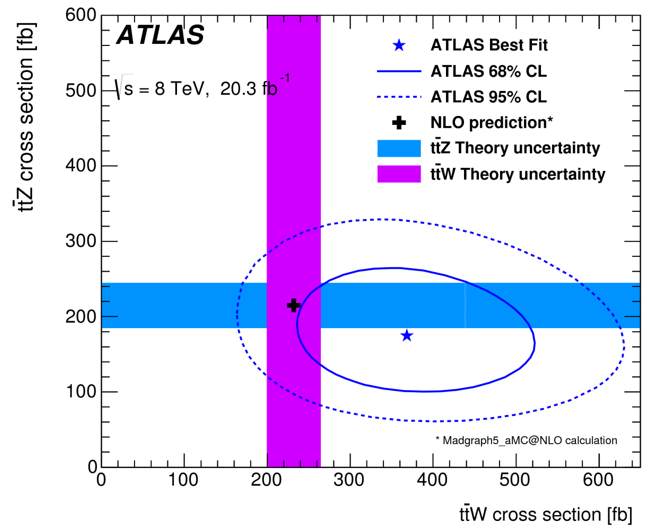
ttW : SS di-muon, Trilepton

ttZ : Trilepton, Tetralepton

ttW, ttZ @ 8 TeV

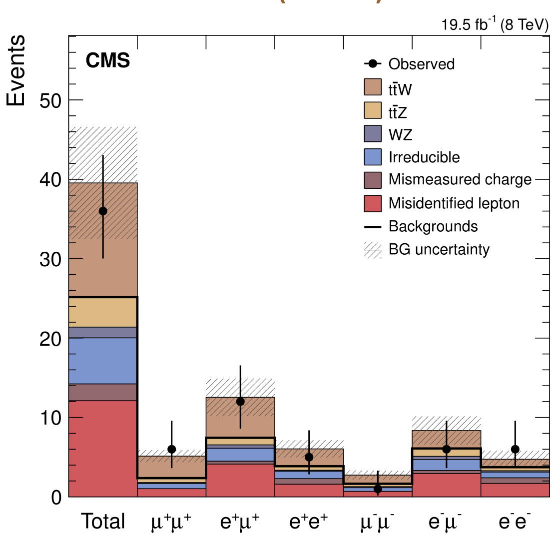
ATLAS: JHEP 11 (2015) 172

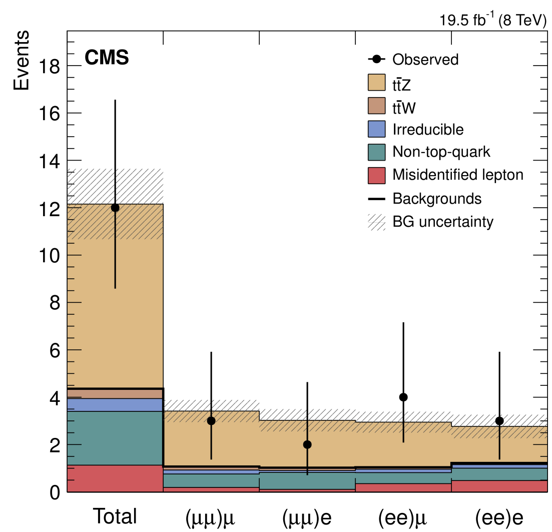


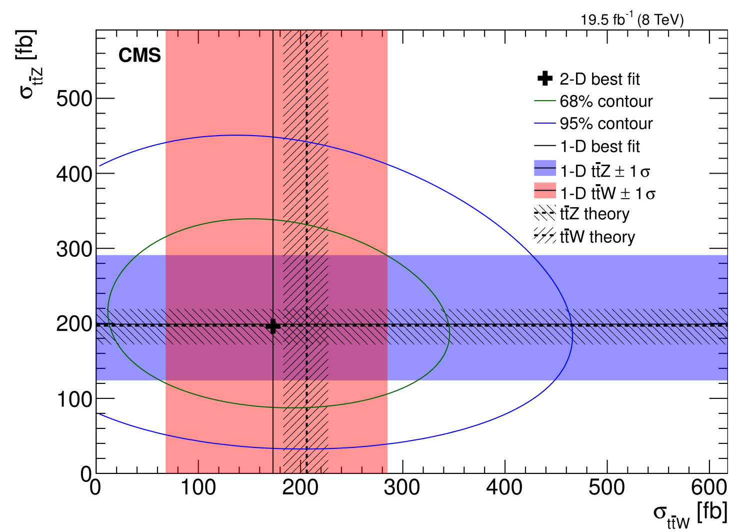


ATLAS: σ_{ttZ} = 369 (+100, -91) fb, σ_{ttW} = 176 (+58, -52) fb

CMS: EPJC 74 (2014) 3060



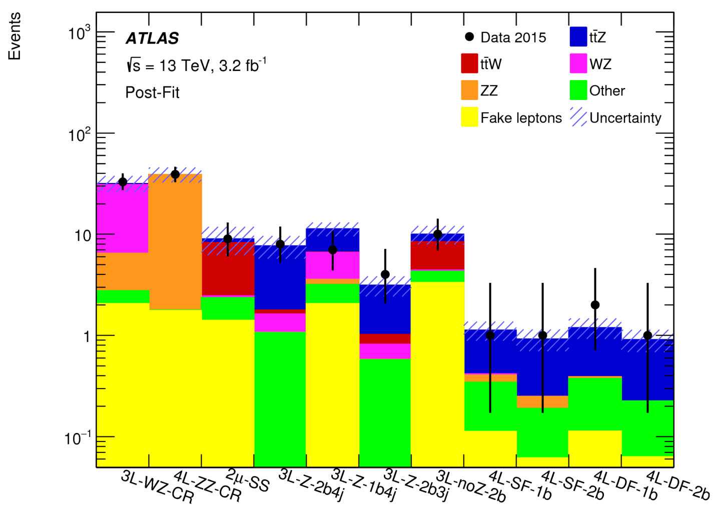


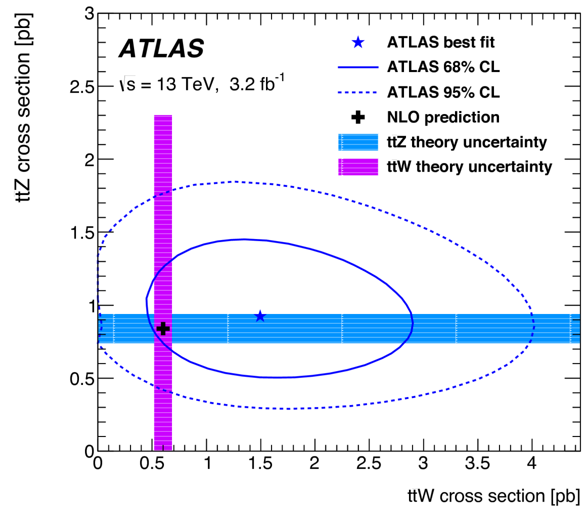


CMS: $\sigma_{ttZ} = 200^{+80}_{-70}$ (stat) $^{+40}_{-30}$ (syst) fb, $\sigma_{ttW} = 170^{+90}_{-80}$ (stat) ±70 (syst) fb

ttW, ttZ @ 13 TeV

ATLAS: arXiv:1609.01599 (Submitted to EPJC) 3.2 fb^{-1} of 2015 data





ATLAS Results:

$\sigma_{ttZ} = 0.9 \pm 0.3$ pb

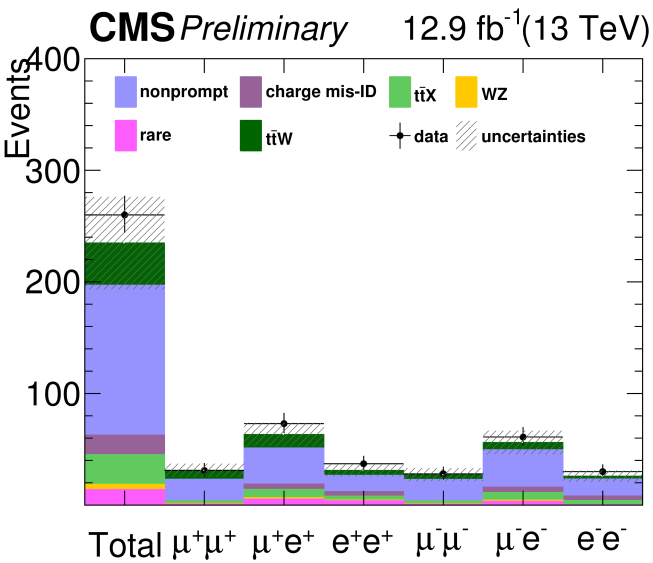
$\sigma_{ttW} = 1.5 \pm 0.8$ pb

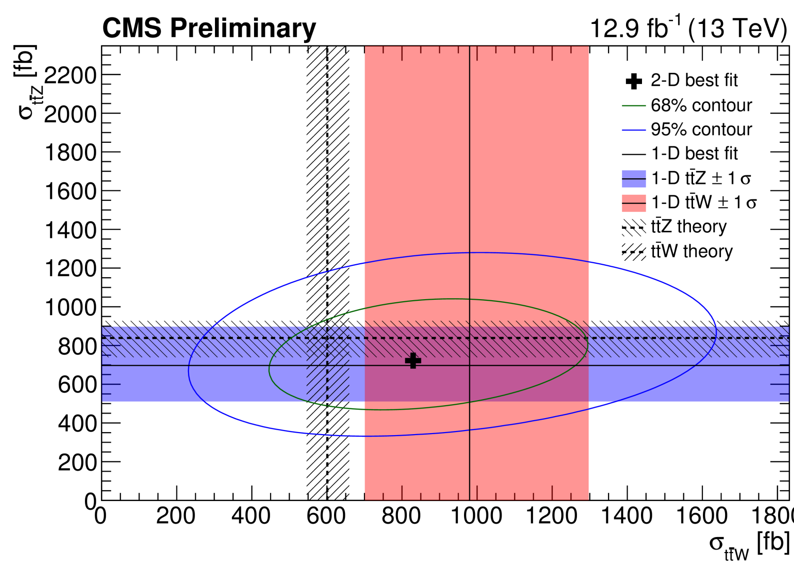
CMS Results:

$\sigma_{ttZ} = 0.7\ ^{+0.16}_{-0.15}$ (stat) $^{+0.14}_{0.12}$ (syst) pb

$\sigma_{ttW} = 0.98\ ^{+0.23}_{-0.22}$ (stat) $^{+0.22}_{-0.18}$ (syst) pb

CMS: CMS-PAS-TOP-16-017 12.9 fb^{-1} of 2016 data





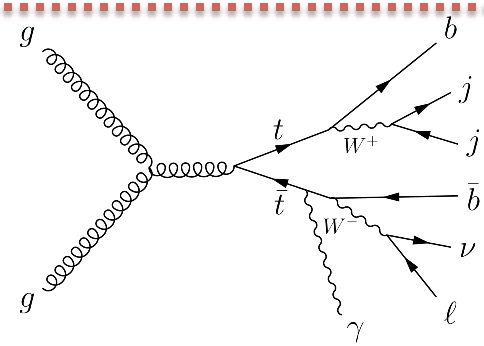
Signal Significance:

ttW: 3.9σ (obs) / 2.6σ (exp)

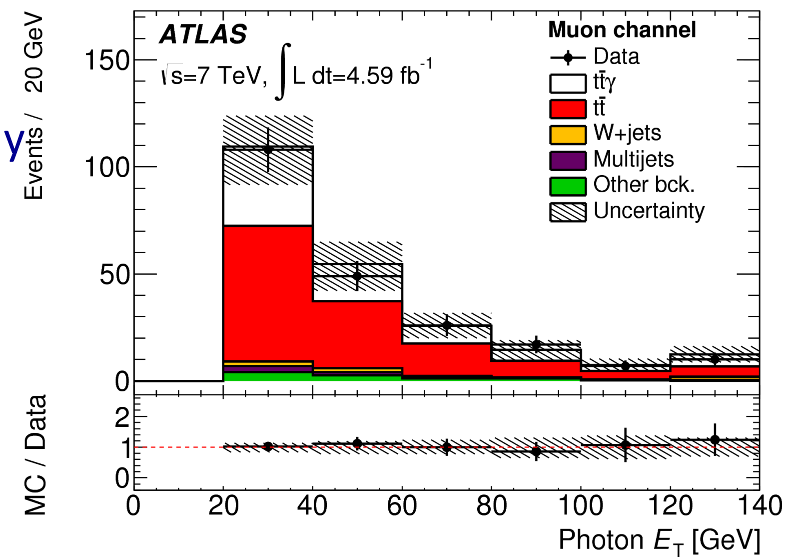
ttZ : 4.6σ (obs) / 5.8σ (exp)

$t\bar{t}\gamma$ @ 7 & 8 TeV

ATLAS (7 TeV): PRD 91, 072007 (2015)
CMS (8 TeV): PAS-TOP-14-008



- The cross section is sensitive to new physics
  - e.g. composite top-quarks or excited top-quark production
- Analysis performed in ttbar semileptonic deacay channel
- Require presence of an isolated photon candidate
- Fiducial cross section measured in semileptonic decay channel
  - Measured relative to ttbar production x-section



ATLAS Results:

$\sigma_{tt\gamma}^{fid}$ x BR = 63 ± 8 (stat) $^{+17}_{-13}$ (syst) ± 1 (lumi) per lepton flavour

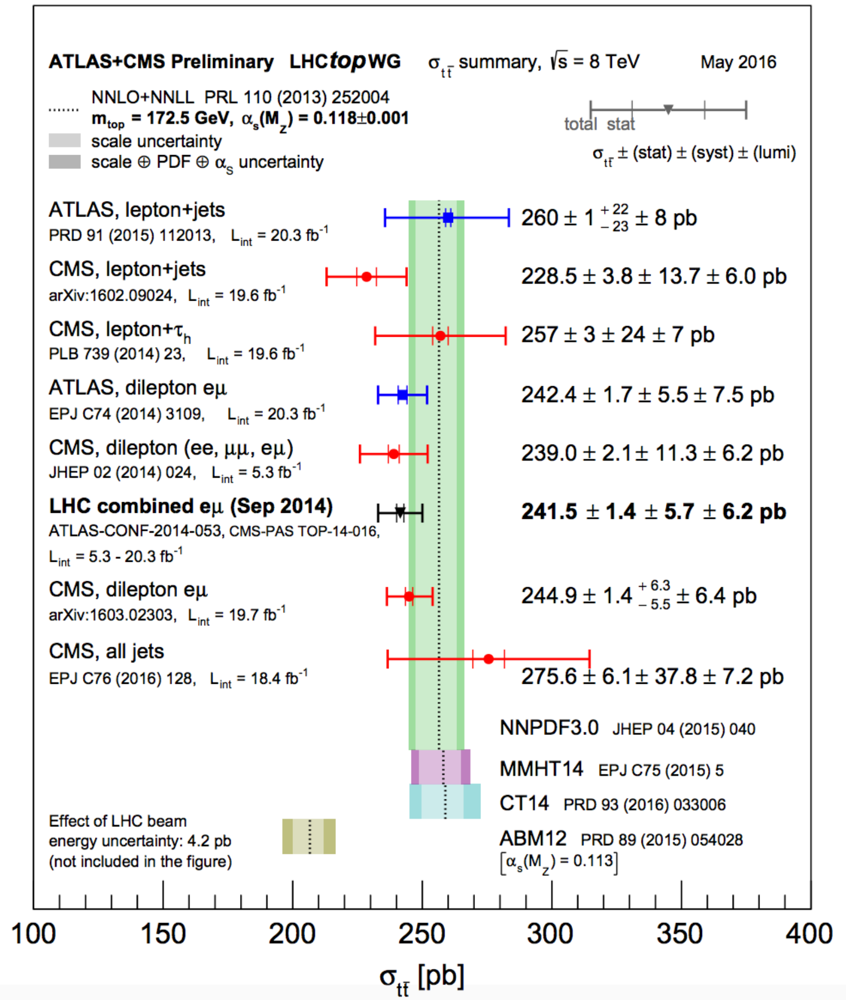
CMS Results:

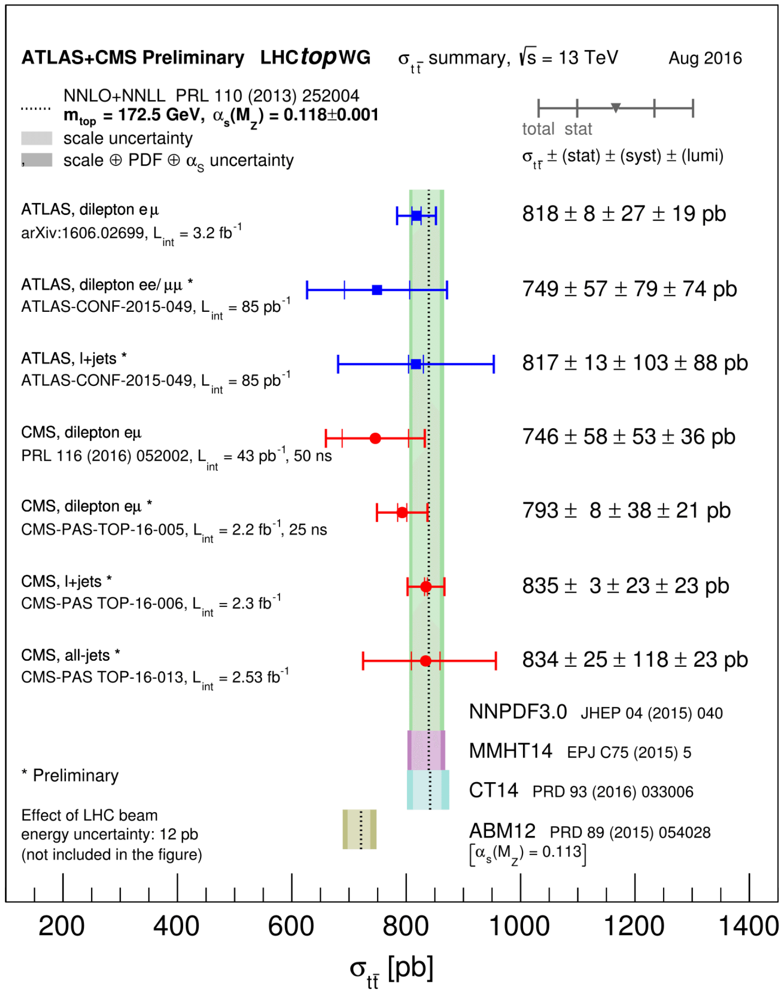
Category	R	$\sigma^{\mathrm{fid}}_{\mathrm{t\bar{t}}+\gamma}$ (fb)	$\sigma_{\mathrm{t\bar{t}}+\gamma} \times \mathcal{B}$ (fb)
e+jets	$(5.7 \pm 1.8) \times 10^{-4}$	139 ± 45	582 ± 187
μ+jets	$(4.7 \pm 1.3) \times 10^{-4}$	115 ± 32	453 ± 124
Combination	$(5.2 \pm 1.1) \times 10^{-4}$	127 ± 27	515 ± 108
Theory	-	-	$592 \pm 71(\mathrm{scale}) \pm 30(\mathrm{PDF})$

$R = \sigma_{tt+\gamma}/\sigma_{tt}$
$= (5.2 \pm 1.1) \times 10^{-4}$.

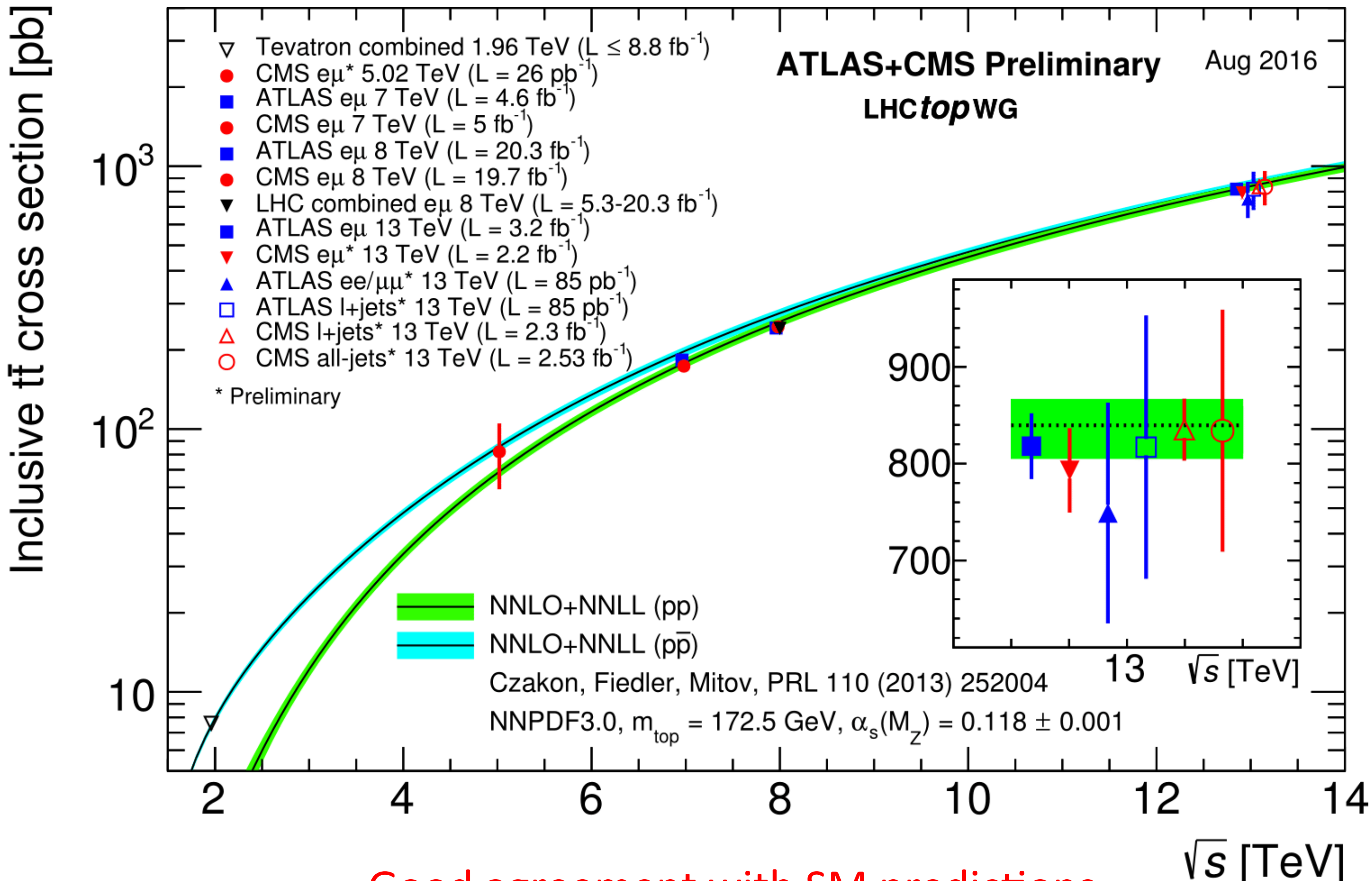
Summary

Summary of ATLAS & CMS Measurements





Summary



Good agreement with SM predictions

More precision expected at 13 TeV with 2016 data

Backup

Uncertainties (eμ, 7 & 8 TeV)

CMS

Source	Uncertainty [%] 7 TeV	8 TeV
Total (vis)	$\pm^{3.6}_{3.4}$	$\pm^{3.7}_{3.4}$
Q^2 scale (extrapol.)	$\mp^{0.0}_{0.4}$	$\pm^{0.2}_{0.1}$
ME/PS matching (extrapol.)	$\pm^{0.1}_{0.1}$	$\pm^{0.3}_{0.3}$
Top p_T (extrapol.)	$\pm^{0.5}_{0.3}$	$\pm^{0.6}_{0.3}$
PDF (extrapol.)	$\pm^{0.2}_{0.1}$	$\pm^{0.2}_{0.1}$
Total	$\pm^{3.6}_{3.5}$	$\pm^{3.7}_{3.5}$

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

Uncertainties (eμ, 7 & 8 TeV)

ATLAS

$\sqrt{s}$ Uncertainty (inclusive $\sigma_{t\bar{t}}$)	7 TeV $\Delta\epsilon_{e\mu}/\epsilon_{e\mu}$ (%)	$\Delta C_b/C_b$ (%)	$\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ (%)	8 TeV $\Delta\epsilon_{e\mu}/\epsilon_{e\mu}$ (%)	$\Delta C_b/C_b$ (%)	$\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ (%)
Data statistics			1.69			0.71
$t\bar{t}$ modelling	0.71	−0.72	1.43	0.65	−0.57	1.22
Parton distribution functions	1.03	-	1.04	1.12	-	1.13
QCD scale choice	0.30	-	0.30	0.30	-	0.30
Single-top modelling	-	-	0.34	-	-	0.42
Single-top/$t\bar{t}$ interference	-	-	0.22	-	-	0.15
Single-top Wt cross-section	-	-	0.72	-	-	0.69
Diboson modelling	-	-	0.12	-	-	0.13
Diboson cross-sections	-	-	0.03	-	-	0.03
Z+jets extrapolation	-	-	0.05	-	-	0.02
Electron energy scale/resolution	0.19	−0.00	0.22	0.46	0.02	0.51
Electron identification	0.12	0.00	0.13	0.36	0.00	0.41
Muon momentum scale/resolution	0.12	0.00	0.14	0.01	0.01	0.02
Muon identification	0.27	0.00	0.30	0.38	0.00	0.42
Lepton isolation	0.74	-	0.74	0.37	-	0.37
Lepton trigger	0.15	−0.02	0.19	0.15	0.00	0.16
Jet energy scale	0.22	0.06	0.27	0.47	0.07	0.52
Jet energy resolution	−0.16	0.08	0.30	−0.36	0.05	0.51
Jet reconstruction/vertex fraction	0.00	0.00	0.06	0.01	0.01	0.03
b-tagging	-	0.18	0.41	-	0.14	0.40
Misidentified leptons	-	-	0.41	-	-	0.34
Analysis systematics ($\sigma_{t\bar{t}}$)	1.56	0.75	2.27	1.66	0.59	2.26
Integrated luminosity	-	-	1.98	-	-	3.10
LHC beam energy	-	-	1.79	-	-	1.72
Total uncertainty ($\sigma_{t\bar{t}}$)	1.56	0.75	3.89	1.66	0.59	4.27

Uncertainty (fiducial $\sigma_{t\bar{t}}^{\text{fid}}$)	$\Delta\epsilon_{e\mu}/\epsilon_{e\mu}$ (%)	$\Delta C_b/C_b$ (%)	$\Delta\sigma_{t\bar{t}}^{\text{fid}}/\sigma_{t\bar{t}}^{\text{fid}}$ (%)	$\Delta\epsilon_{e\mu}/\epsilon_{e\mu}$ (%)	$\Delta C_b/C_b$ (%)	$\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ (%)
$t\bar{t}$ modelling	0.84	−0.72	1.56	0.74	−0.57	1.31
Parton distribution functions	0.35	-	0.38	0.23	-	0.28
QCD scale choice	0.00	-	0.00	0.00	-	0.00
Other uncertainties (as above)	0.88	0.21	1.40	1.00	0.17	1.50
Analysis systematics ($\sigma_{t\bar{t}}^{\text{fid}}$)	1.27	0.75	2.13	1.27	0.59	2.01
Total uncertainty ($\sigma_{t\bar{t}}^{\text{fid}}$)	1.27	0.75	3.81	1.27	0.59	4.14

Uncertainty eμ + jets (5.02 TeV) [CMS-PAS-TOP-16-015]

Source	$\Delta\sigma_{t\bar{t}}$ (pb)	$\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ (%)
Electron efficiencies	1.1	1.4
Muon efficiencies	2.4	3.0
Jet energy scale	1.1	1.3
Jet energy resolution	0.05	0.06
QCD scales of $t\bar{t}$ signal (PS)	1.0	1.2
QCD scales of $t\bar{t}$ signal (ME)	0.2	0.2
Hadronization model of $t\bar{t}$ signal	1.0	1.2
PDF	0.4	0.5
MC statistics	1.2	1.4
t W background	1.1	1.3
WV background	0.5	0.6
DY background	2.1	2.6
Non W/Z background	1.9	2.3
Total systematic (w/o luminosity)	4.6	5.6
Integrated luminosity	9.8	12
Statistical uncertainty	20	24
Total	23	28

Uncertainties

(eμ, 13TeV)

ATLAS

Uncertainty (inclusive $\sigma_{t\bar{t}}$)	$\Delta\epsilon_{e\mu}/\epsilon_{e\mu}$ [%]	$\Delta C_b/C_b$ [%]	$\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ [%]
Data statistics			0.9
$t\bar{t}$ NLO modelling	0.7	−0.1	0.8
$t\bar{t}$ hadronisation	−2.4	0.4	2.8
Initial- and final-state radiation	−0.3	0.1	0.4
$t\bar{t}$ heavy-flavour production	-	0.4	0.4
Parton distribution functions	0.5	-	0.5
Single-top modelling	-	-	0.3
Single-top/$t\bar{t}$ interference	-	-	0.6
Single-top Wt cross-section	-	-	0.5
Diboson modelling	-	-	0.1
Diboson cross-sections	-	-	0.0
Z+jets extrapolation	-	-	0.2
Electron energy scale/resolution	0.2	0.0	0.2
Electron identification	0.3	0.0	0.3
Electron isolation	0.4	-	0.4
Muon momentum scale/resolution	−0.0	0.0	0.0
Muon identification	0.4	0.0	0.4
Muon isolation	0.2	-	0.3
Lepton trigger	0.1	0.0	0.2
Jet energy scale	0.3	0.1	0.3
Jet energy resolution	−0.1	0.0	0.2
b-tagging	-	0.1	0.3
Misidentified leptons	-	-	0.6
Analysis systematics	2.7	0.6	3.3
Integrated luminosity	-	-	2.3
LHC beam energy	-	-	1.5
Total uncertainty	2.7	0.6	4.4

Uncertainty (fiducial $\sigma^{\mathrm{fid}}_{t\bar{t}}$)	$\Delta G_{e\mu}/G_{e\mu}$ [%]	$\Delta C_b/C_b$ [%]	$\Delta\sigma^{\mathrm{fid}}_{t\bar{t}}/\sigma^{\mathrm{fid}}_{t\bar{t}}$ [%]
$t\bar{t}$ NLO modelling	0.5	−0.1	0.6
$t\bar{t}$ hadronisation	−1.6	0.4	1.9
Parton distribution functions	0.1	-	0.1
Other uncertainties (as above)	0.8	0.4	1.5
Analysis systematics ($\sigma^{\mathrm{fid}}_{t\bar{t}}$)	1.8	0.6	2.5
Total uncertainty ($\sigma^{\mathrm{fid}}_{t\bar{t}}$)	1.8	0.6	3.9

Uncertainties

(eμ, 13TeV)

CMS

Source	$\Delta\sigma_{t\bar{t}}$ (pb)	$\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ (%)
Experimental		
Trigger efficiencies	9.7	1.2
Lepton efficiencies	18.3	2.3
Lepton energy scale	<1	≤ 0.1
Jet energy scale	16.9	2.1
Jet energy resolution	0.8	0.1
b tagging	10.6	1.3
Mistagging	<1	≤ 0.1
Pileup	1.4	0.2
Modeling		
μ_F and μ_R scales	<1	≤ 0.1
$t\bar{t}$ NLO generator	16.8	2.1
$t\bar{t}$ hadronization	5.9	0.7
Parton shower scale	6.3	0.8
PDF	4.8	0.6
Background		
Single top quark	11.8	1.5
VV	<1	≤ 0.1
Drell–Yan	<1	≤ 0.1
Non-W/Z leptons	2.5	0.3
$t\bar{t}V$	<1	≤ 0.1
Total systematic (no integrated luminosity)	36.8	4.6
Integrated luminosity	21.4	2.7
Statistical	8.3	1.0
Total	43.4	5.5