

Measurements of $t\bar{t} + X$ with the ATLAS and CMS Experiments

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DESY

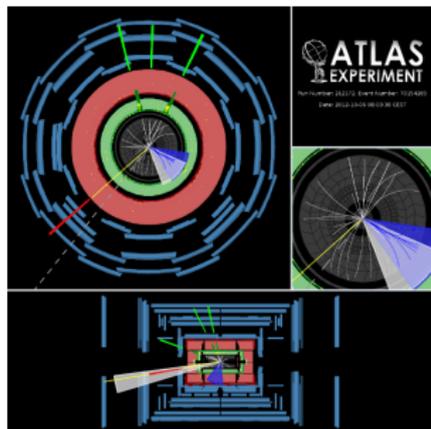
31.08.2015



The top quark: key to QCD, EWK, Higgs and new physics

Why $t\bar{t}+X$?

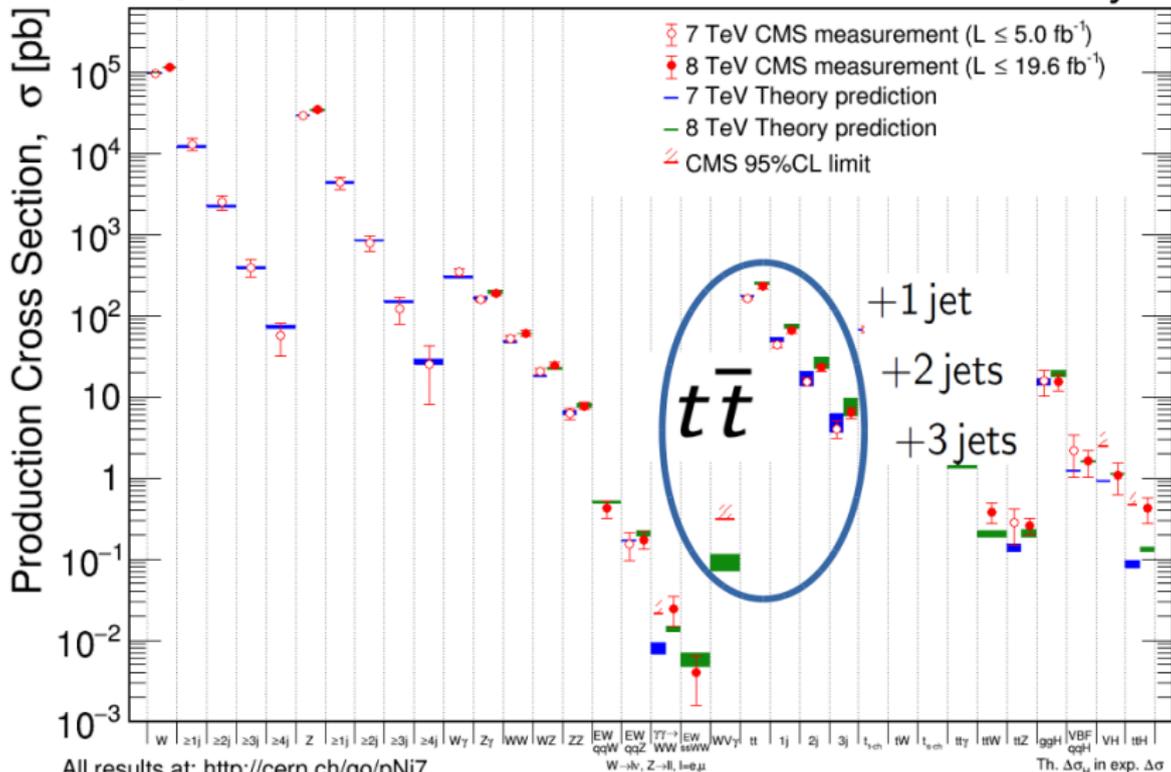
- About half of $t\bar{t}$ events contain additional energetic jets
 - Possibility to test higher order QCD calculations
 - Background for $t\bar{t}H$
 - Anomalous production of $t\bar{t}$ +jets could reveal new physics
- $t\bar{t}$ + heavy flavour jets
 - Test of NLO QCD calculations
 - Irreducible background for $t\bar{t}H(bb)$
- $t\bar{t}+W/Z/\gamma$ are rare processes in the SM
 - Allow direct access to EW couplings of top quark
 - Potential to verify if couplings are compatible with SM or altered by BSM effects
 - Also important background for $t\bar{t}H$
 - First evidence on the coupling come from the production rate



$t\bar{t}$ +jets (including $t\bar{t}+b\bar{b}$)

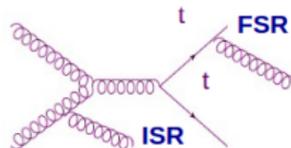
July 2015

CMS Preliminary

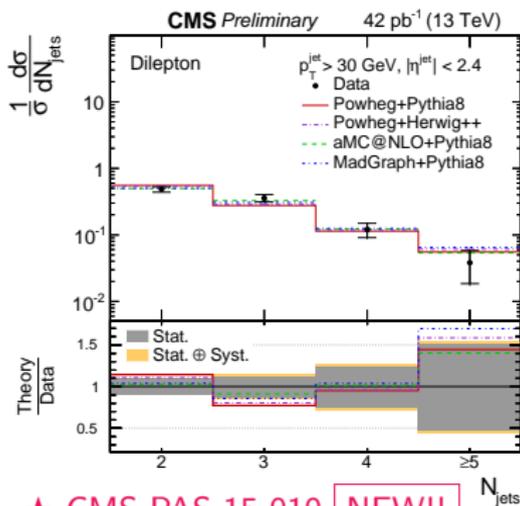


$t\bar{t}$ +jets

- Large fraction of $t\bar{t}$ produced with high energetic jets from ISR/FSR
 - Additional jets cannot be unambiguously associated with the top or initial-state quark from which they originate



- Stringent test of QCD perturbation series to higher orders
- Typically, large uncertainty due to radiation modelling in MC: Help tuning MC models with measurements
- Studied by measuring jet multiplicity in the event, properties of the additional jets in different kinematic ranges
- Correction of detector level effects through "unfolding" to particle level
- Measurements performed in fiducial volume ("visible") to minimize model dependencies



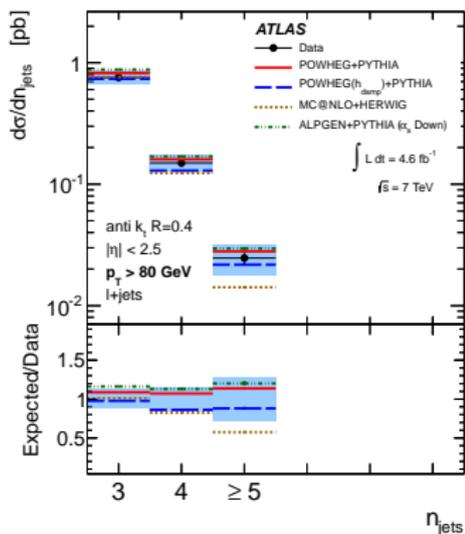
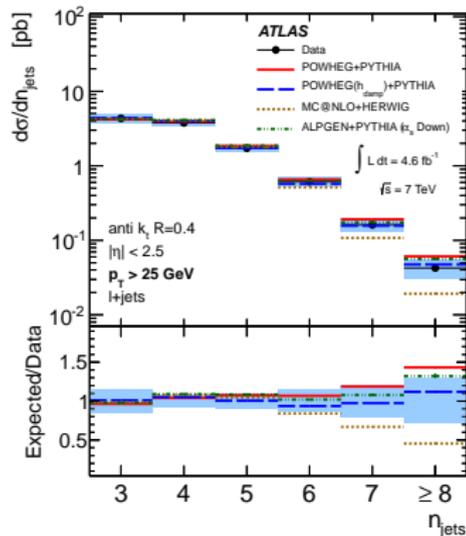
Jet Multiplicity (l+jets)

[JHEP 1501 (2015) 020]

ATLAS: differential cross section, 7 TeV

Comparison between generation at LO with up to 5 hard partons with NLO computation with most jets from the parton shower.

- Largest uncertainties: JES and MC modeling
- Measurement dominated by statistical uncertainty at high jet multiplicities
- Model differences increase with jet multiplicities and jet p_T threshold
- Data have discriminant power between models

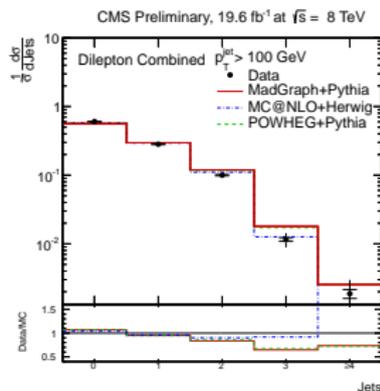
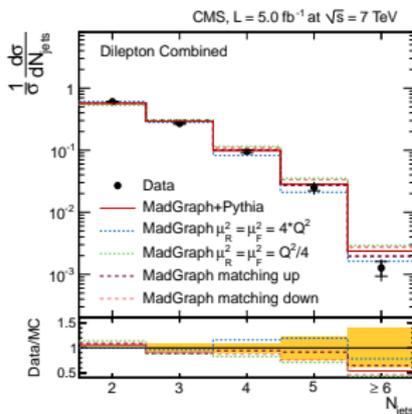
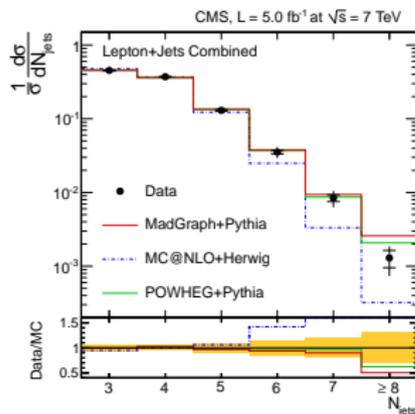


Jet Multiplicity

[EPJ C74 (2015) 3014, CMS-PAS-TOP-12-041]

CMS, 7 and 8 TeV

- Normalized differential cross section in l+jets and dilepton channels (7 and 8 TeV), thresholds up to 100 GeV
- Compared to different MCs and varied parameters



- Consistent results between the channels and \sqrt{s}
- Uncertainties of l+jets measurement at high jet multiplicities (7 TeV) similar to ATLAS

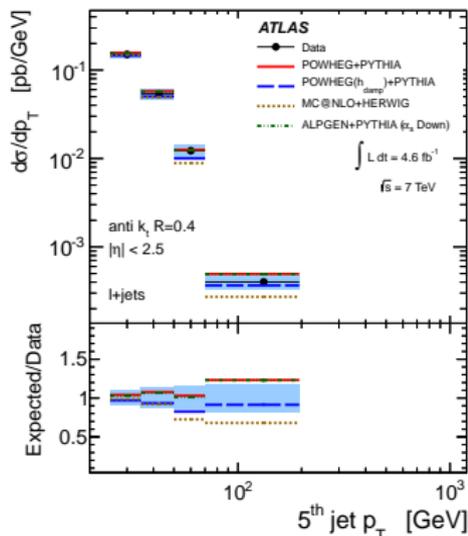
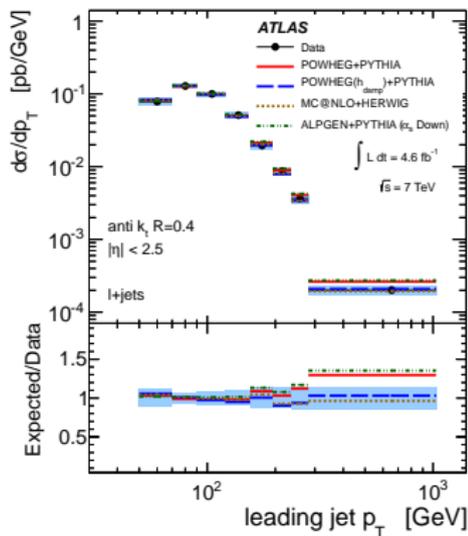
Diff. cross section: Jet p_T in $t\bar{t}$

ATLAS [JHEP 1501 (2015) 020]

Diff. cross section as a function of jet p_T (l+jets channel, 7TeV)

Ordered jets in p_T and unfold single spectrum

- Additional requirement: leading jet $p_T > 50$ GeV, subleading jet $p_T > 35$ GeV
- Leading jet: high probability from top decay
- 5th jet: additional radiation

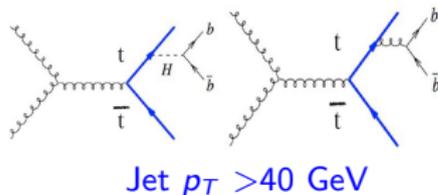
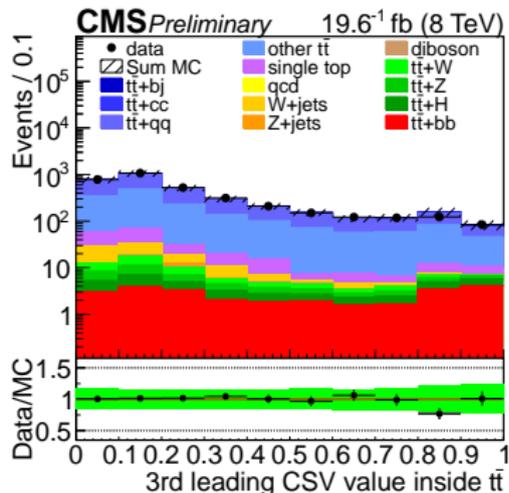


- Powheg with $h_{damp} = m_t$ preferred by data

$t\bar{t}b\bar{b}$: e/μ + jets

[CMS PAS-TOP-13-016 (2015)]

- Irreducible non resonant background in the search for $t\bar{t}H(b\bar{b})$
- Test validity of NLO QCD calculations
- Measurement of ratio $\sigma(t\bar{t}b\bar{b})/\sigma(t\bar{t}jj)$: large uncertainties cancellation
 - ◇ Selection: one isolated lepton, ≥ 4 jets, ≥ 2 b-tagged jets
 - ◇ Signal extraction by fit to the measured b-tagging discriminator
 - ◇ Jet flavour at gen level defined by leading quark flavour (parton) or presence of B hadron (particle)



$$\frac{\sigma(t\bar{t}b\bar{b})}{\sigma(t\bar{t}jj)}^{hardB} = 0.0117 \pm 0.0040(\text{stat.}) \pm 0.0003(\text{ syst.})$$

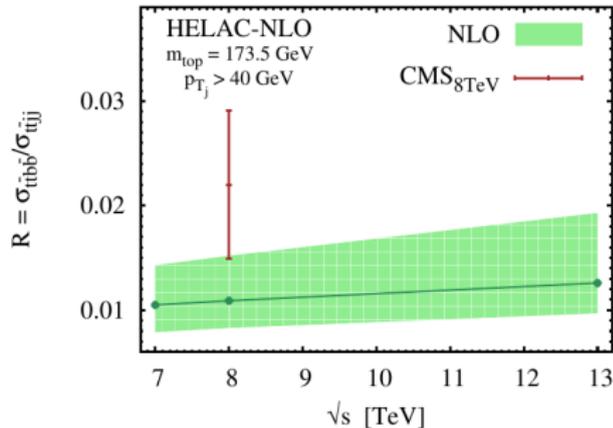
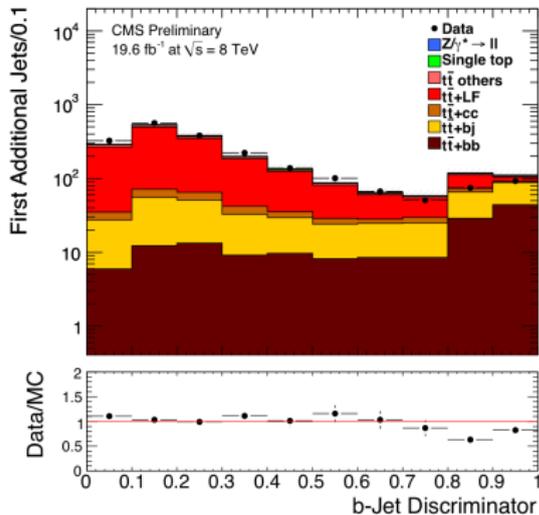
$$\frac{\sigma(t\bar{t}b\bar{b})}{\sigma(t\bar{t}jj)}^{hadronB} = 0.0151 \pm 0.0049(\text{stat.}) \pm 0.0004(\text{ syst.})$$

$$\left(\frac{\sigma(t\bar{t}b\bar{b})}{\sigma(t\bar{t}jj)}\right)^{NLO} = 0.0109^{+0.0043}_{-0.0026} \text{ [arXiv:1403.2046]}$$

$t\bar{t}$ + $b\bar{b}$: dilepton

[CMS Phys.Lett. B746 (2015)]

- Selection: dilepton events with ≥ 4 jets, ≥ 2 b-tagged jets
- Signal extraction by fit to the measured b-tagging algorithm discriminators
- Corrected to particle level



Comparison with NLO QCD calculations

[arXiv:1403.2046v3]

$$\frac{\sigma(t\bar{t}b\bar{b})}{\sigma(t\bar{t}jj)} = 0.022 \pm 0.004(\text{stat.}) \pm 0.005(\text{sys.}) \text{ for } 40 \text{ GeV}$$

MadGraph (Powheg): 0.013 (0.014)

$t\bar{t}+b\bar{b}, t\bar{t}+b$

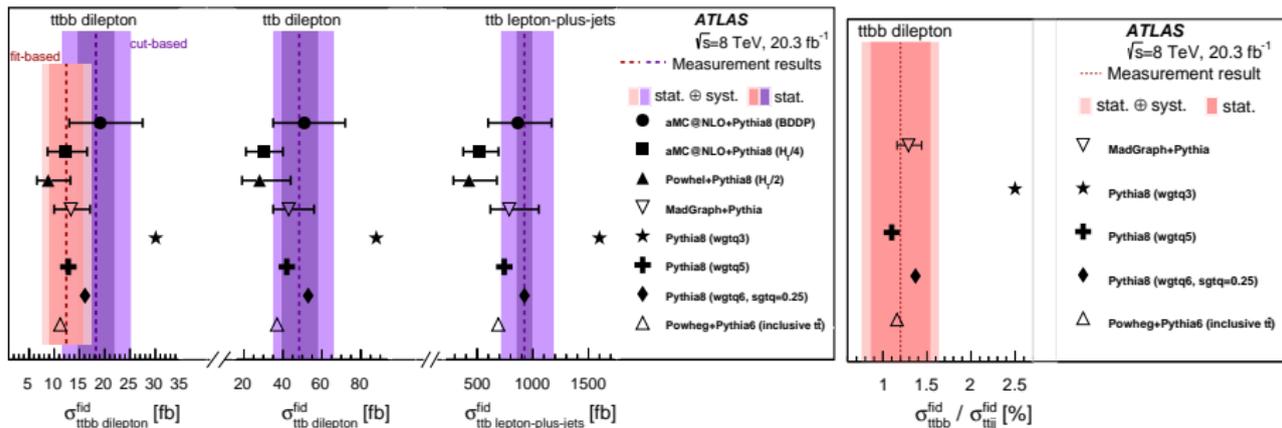
ATLAS arXiv:1508.06868

NEW!!

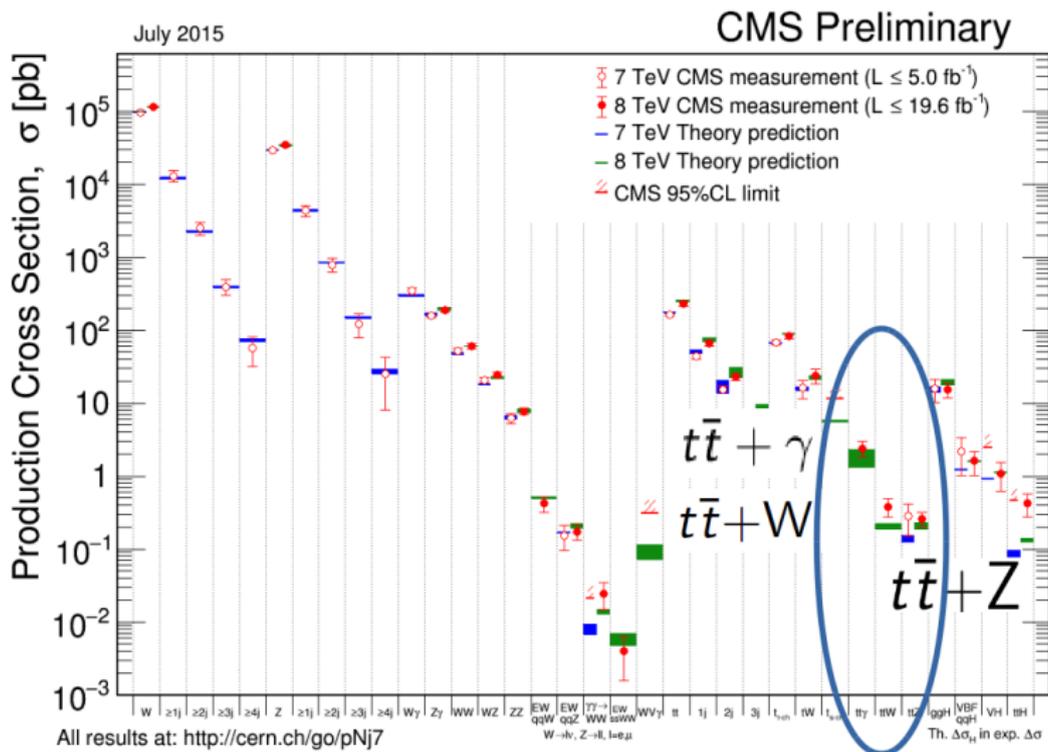
- Cut-based and fit-based analyses for $t\bar{t}+b\bar{b}$ in dilepton channel

$$\frac{\sigma(t\bar{t}b\bar{b})}{\sigma(t\bar{t}jj)} = 0.0130 \pm 0.0033(\text{stat.}) \pm 0.0028(\text{syst.})$$

- Fiducial measurements of $t\bar{t}+b$ in $l+l$ jets and $e\mu$ channels
- Additionally checked subtraction of $t\bar{t}V/H$ and comparison with QCD-only predictions
- Comparison with different $g \rightarrow b\bar{b}$ splitting models

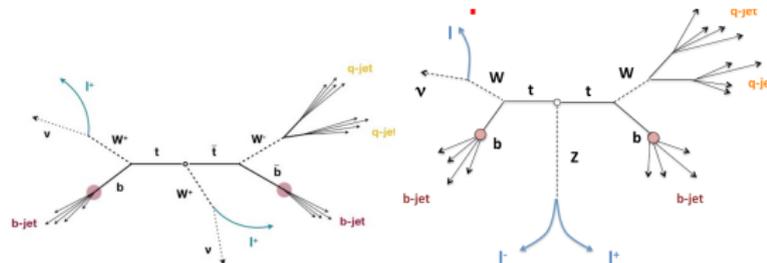
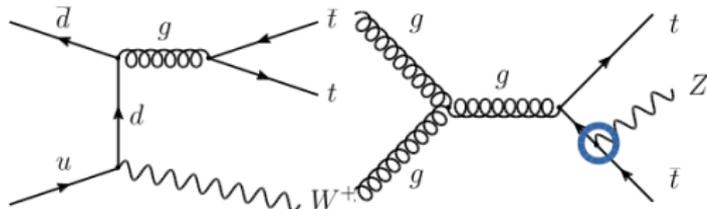


$t\bar{t}$ in association with bosons



$t\bar{t}+W/Z$

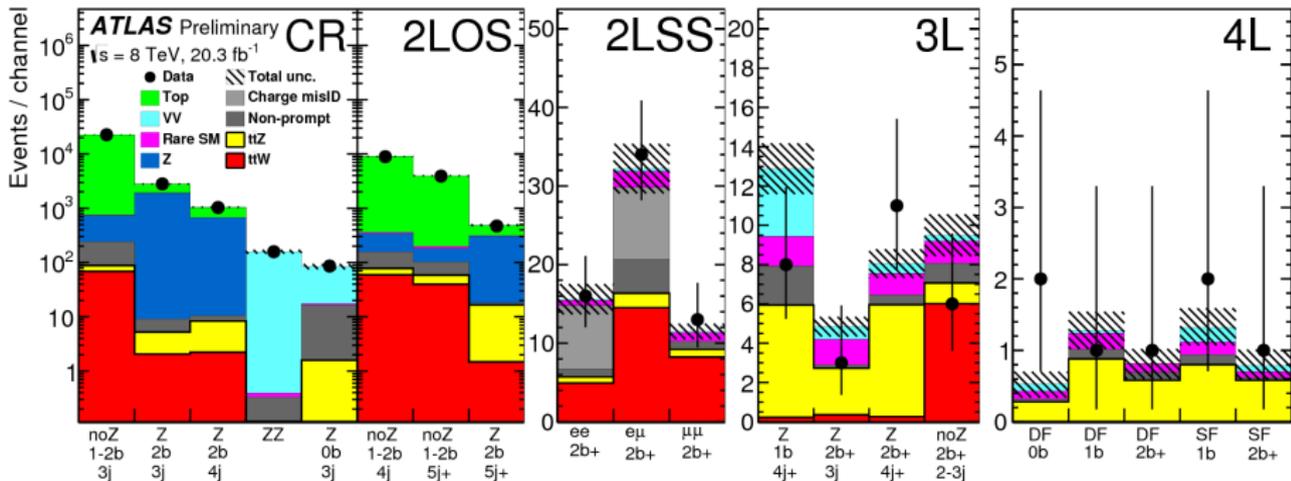
- Measure couplings to bosons
- Important background for BSM searches
- Analyses are performed in bins of the number of selected leptons (2,3,4)
- Different number of leptons \rightarrow different admixture of $t\bar{t}W$ and $t\bar{t}Z$ processes
 - Same-sign dilepton analysis: $t\bar{t}+W$
 - Tripleton and Four-lepton analysis: $t\bar{t}+Z$ process



$t\bar{t}+W/Z$

[ATLAS-CONF-2015-032]

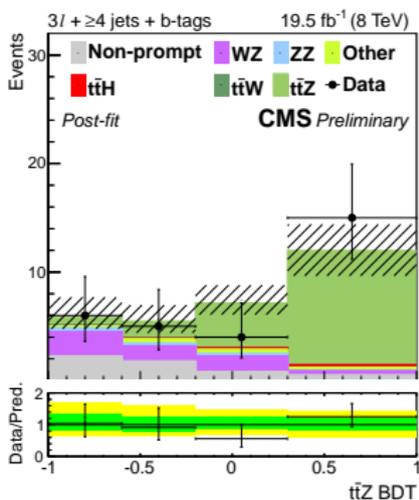
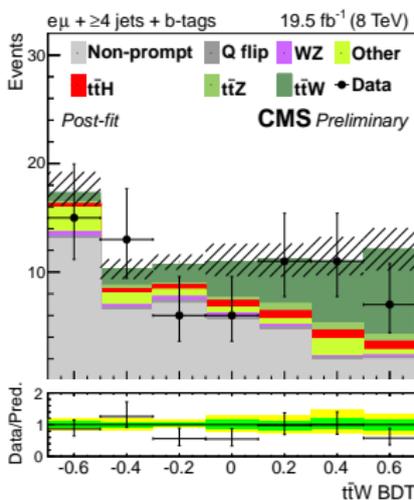
- Four signal regions: opposite sign (OS) dilepton, same sign (SS) dilepton, trilepton, tetralepton.
- Fit for $t\bar{t}Z$ and $t\bar{t}W$ simultaneously in a binned likelihood fit
- Further split into categories depending on jet multiplicity, number of b-tagged jets and E_T^{miss} , optimised individually to increase sensitivity.

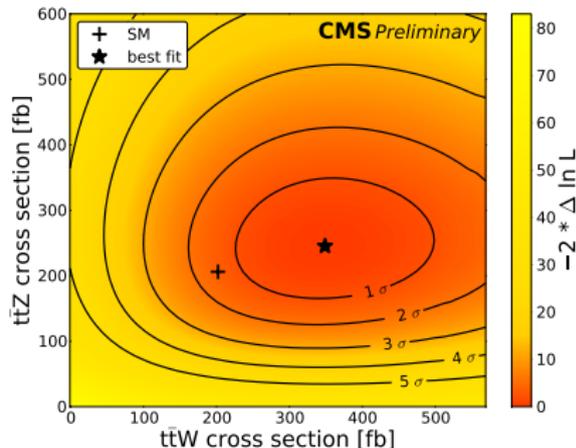
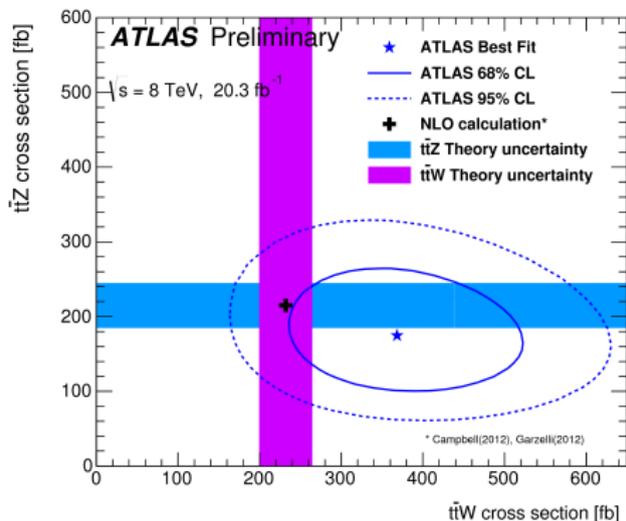


$t\bar{t}+W/Z$

[CMS PAS TOP-14-021 (2015)]

- Also performed in many channels with different numbers of leptons, jets and b tags
- Additionally: perform event reconstruction by matching jets and leptons to W/Z bosons and top quarks
 - Combine into linear discriminant
 - Choose best permutation
- Combine resulting match scores with kinematic quantities in BDTs



$t\bar{t}+W/Z$ Results: ATLAS & CMS

- $\sigma(ttW) = 369_{-91}^{+100} \text{ fb} - 5.0\sigma \text{ obs. (3.2 exp)}$

- $\sigma(ttZ) = 176_{-52}^{+58} \text{ fb} - 4.2\sigma \text{ obs. (4.5 exp)}$

- $\sigma(ttW) = 382_{-102}^{+117} \text{ fb} - 4.8\sigma \text{ obs. (3.5 exp)}$

- $\sigma(ttZ) = 242_{-55}^{+65} \text{ fb} - 6.0\sigma \text{ obs. (5.7 exp)}$

→ Associated $t\bar{t}+W/Z$ production established

$t\bar{t} + \gamma$: l+jets, 7TeV

[ATLAS PRD 91 (2015)07207]

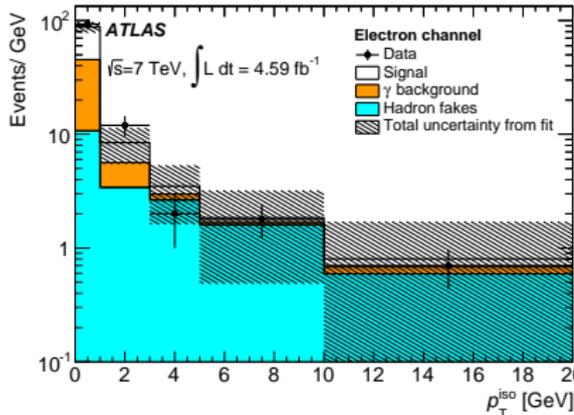
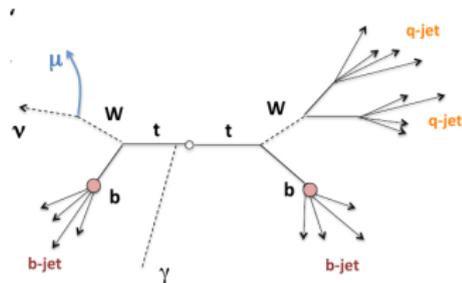
Sensitive to $t\gamma$ coupling and models with composite top quarks and excited top quark production ($t^* \rightarrow t\gamma$)

- Selection: l+jets + high E_T photon ($E_T > 20$ GeV)
- Suppress misidentified γ : $|m_{e\gamma} - m_Z| > 5$ GeV
- Prompt photons estimated from template fit to photon isolation variable
- Largest systematic uncertainty: jet energy scale
- Fiducial cross section:
 $\sigma_{t\bar{t}+\gamma} \cdot BR = 63 \pm 8(\text{stat})_{-13}^{+17}(\text{syst}) \pm 1(\text{lumi})$ fb
 per lepton flavour

Consistent with SM expectation
 $(\sigma(t\bar{t} + \gamma) = 48 \pm 10 \text{fb})$.

→ Null hypothesis excluded at $\sigma=5.3$ obs.

★ CMS measurement in μ +jets: CMS-PAS-TOP-13-011



Summary

Run I: gained a lot in understanding of $t\bar{t}$ production

- Presented $t\bar{t}$ production with additional jet activity in the $l+jets$ and in the dilepton channels, compared to different MCs and varied parameters
 - In general, good agreement between data-MC
- $t\bar{t}+$ heavy flavour: Irreducible non-resonant background for ttH ($H \rightarrow bb$) analysis
 - Measurements dominated by statistical uncertainty
- Observation of $t\bar{t} + \gamma$, $t\bar{t}+W/Z$, potential to verify if couplings to the top quark are compatible with SM or altered by BSM effects
- All results so far in agreement with SM predictions

Some prospects for Run II

- Achieve necessary statistics to measure the couplings of the top quark to Z, γ
- With more data: explore gg/qq production, use $t\bar{t}+W$ as tag for qq production

BACK UP