Top quark pair production in association with bosons ($t\bar{t}V$, $V=W/Z/$photon) at the LHC

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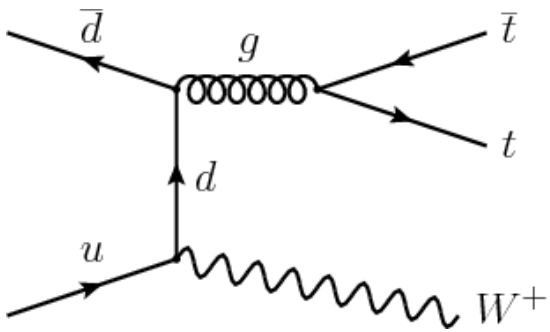
June 16, 2016

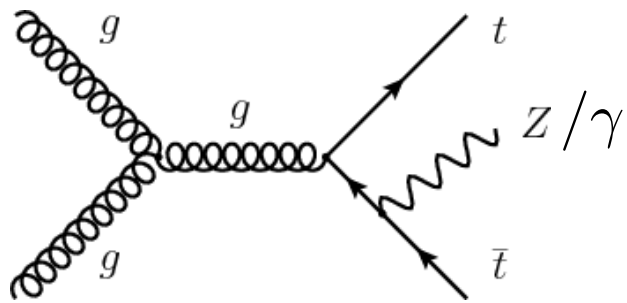
Introduction

- Measurement of $t\bar{t}Z$ and $t\bar{t}\gamma$ is a direct test of the top-EWK couplings (EWK gauge boson couplings are poorly known; their deviation from SM is a signature to new physics)
- $t\bar{t}V$ is an important background for the top-Higgs coupling measurements and many BSM analyses (especially those searching for signals with two or more leptons)

$t\bar{t}W$



$t\bar{t}Z/\gamma$



Run 1 $t\bar{t}V$ analyses

Published:

- ATLAS 8 TeV $t\bar{t}W/Z$ analysis (JHEP 11 (2015) 172)
- CMS 8 TeV $t\bar{t}W/Z$ analysis (JHEP 01 (2016) 096)
- ATLAS 7 TeV $t\bar{t}\gamma$ analysis (PRD 91 (2015) 072007)

Preliminary:

- CMS 8 TeV $t\bar{t}\gamma$ analysis (CMS-PAS-TOP-13-011)

Run 1 $t\bar{t}W/Z$ analysis

ATLAS 8 TeV analysis (20.3 fb^{-1})

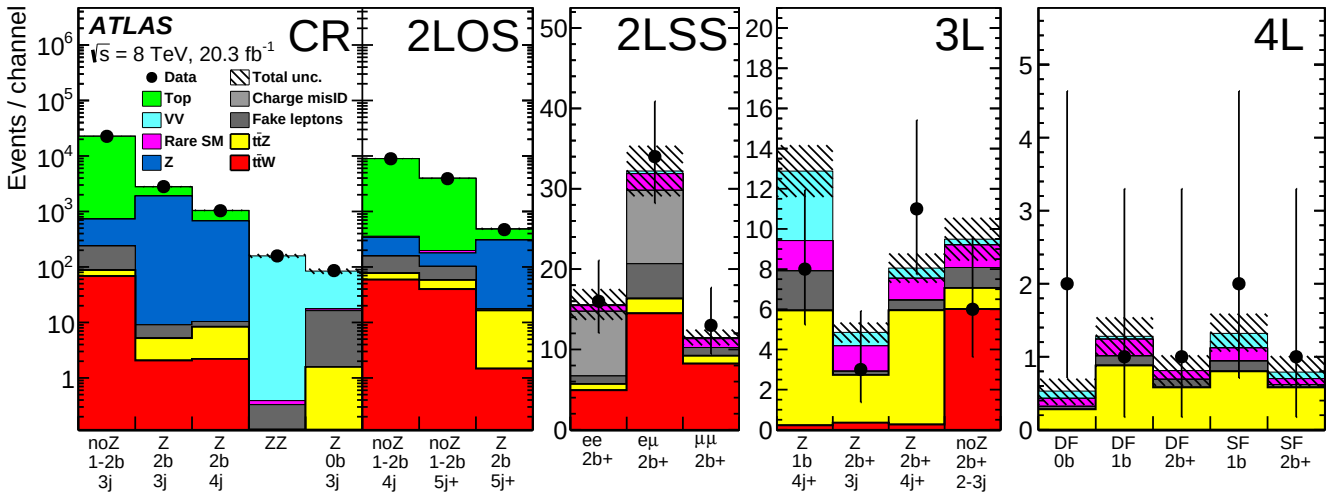
- Four final states: 2LOS, 2LSS, 3L, 4L
  - 2LOS: split regions by Z/noZ, N_{jets}, N_{bjets}, train neural network for each region
  - 2LSS: split into ee, $e\mu$, $\mu\mu$, bin by $N_{\mathrm{jets}} \otimes E_{\mathrm{T}}^{\mathrm{miss}}$
  - 3L: split regions by Z/noZ, N_{jets}, N_{bjets}
  - 4L: choose the best Z candidate, split regions by N_{bjets} and relative flavour of two remaining leptons
- Control regions are defined to constrain main backgrounds: $t\bar{t}$ (2LOS), Z+jets (2LOS), WZ (3L) and ZZ (4L)

CMS 8 TeV analysis (19.5 fb^{-1})

- Four final states: 2LOS, 2LSS, 3L, 4L
  - 2LOS: split regions by lepton flavour, N_{jets}
  - 2LSS: split regions by lepton flavour, N_{jets}
  - 3L: split regions by Z/noZ, N_{jets}
  - 4L: split regions by number of Z candidates (1, ≥ 2)
- For each region, train BDT using a linear discriminant that matches leptons and jets to $t\bar{t}W/Z$ system, and other kinematic variables

ATLAS Run 1 $t\bar{t}W/Z$ analysis: JHEP 11 (2015) 172

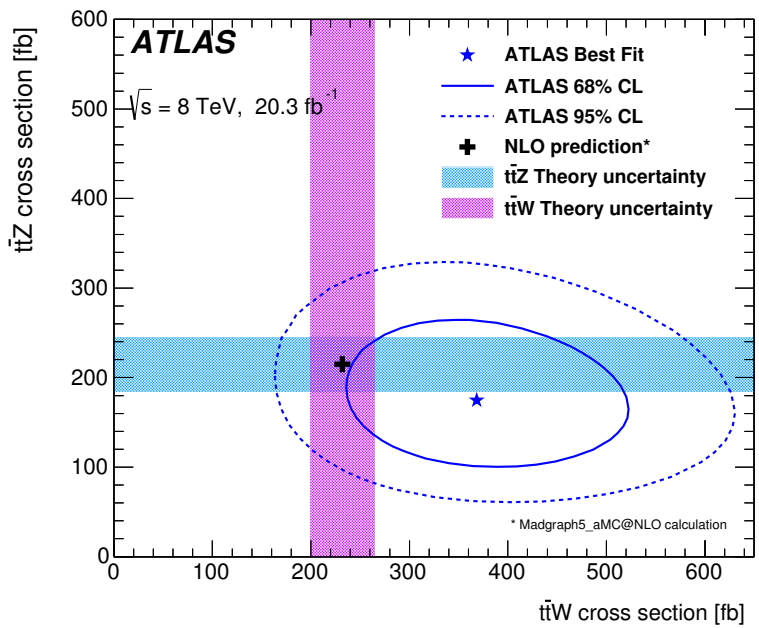
- $\sigma_{t\bar{t}W}$ and $\sigma_{t\bar{t}Z}$ are simultaneously extracted using a maximum likelihood fit over 5 control regions and 15 signal regions



- $\sigma_{t\bar{t}W}^{ATLAS} = 369^{+100}_{-91}$ fb $(\sigma_{t\bar{t}W}^{NLO} = 232 \pm 32\,\text{fb})$
- $\sigma_{t\bar{t}Z}^{ATLAS} = 176^{+58}_{-52}$ fb $(\sigma_{t\bar{t}Z}^{NLO} = 215 \pm 30\,\text{fb})$

Statistical uncertainties dominate

Channel	$t\bar{t}W$ significance Expected	$t\bar{t}W$ significance Observed	$t\bar{t}Z$ significance Expected	$t\bar{t}Z$ significance Observed
2ℓOS	0.4σ	0.1σ	1.4σ	1.1σ
2ℓSS	2.8σ	5.0σ	-	-
3ℓ	1.4σ	1.0σ	3.7σ	3.3σ
4ℓ	-	-	2.0σ	2.4σ
Combined	3.2σ	5.0σ	4.5σ	4.2σ



CMS Run 1 $t\bar{t}W/Z$ analysis: JHEP 01 (2016) 096

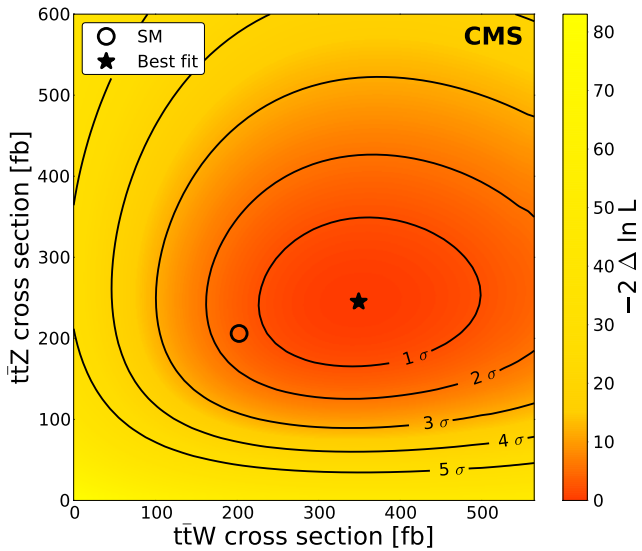
- Extract $t\bar{t}W$ cross section using 2LSS and 3L no$Z$ regions

	Cross sections (fb)	Significance (σ)	
Channel	Observed	Expected	Observed
2ℓSS	414^{+135}_{-112}	3.4	4.9
3ℓ	210^{+225}_{-203}	1.0	1.0
Combined	382^{+117}_{-102}	3.5	4.8

- Extract $t\bar{t}Z$ cross section using 2LOS, 3L Z and 4L regions

	Cross sections (fb)	Significance (σ)	
Channel	Observed	Expected	Observed
2ℓOS	257^{+158}_{-129}	1.8	2.1
3ℓ	257^{+85}_{-67}	4.6	5.1
4ℓ	228^{+150}_{-107}	2.7	3.4
Combined	242^{+65}_{-55}	5.7	6.4

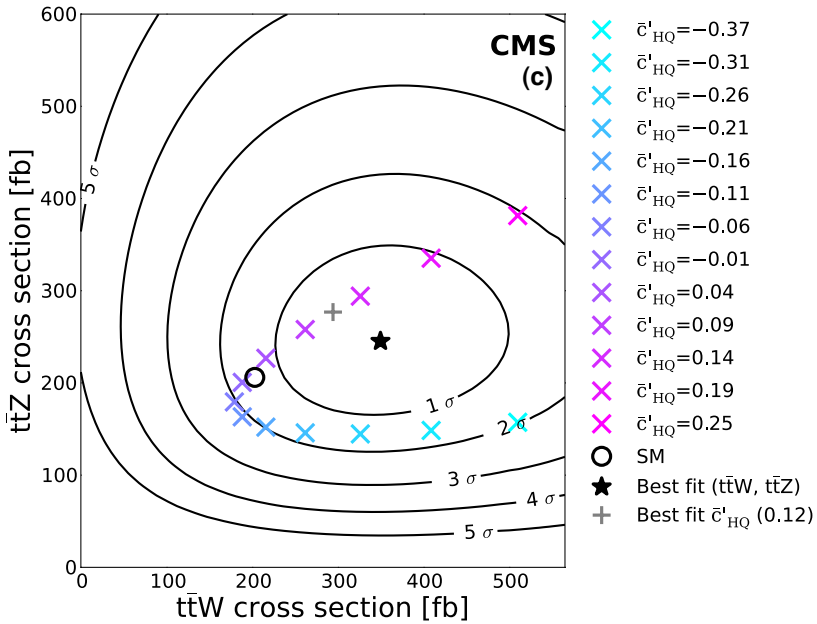
- Extract both cross sections using all regions



Statistical uncertainties dominate

CMS Run 1 $t\bar{t}W/Z$ analysis: JHEP 01 (2016) 0969

- Study constraints on 5 dimension-six operators, which affects $t\bar{t}W/Z$ cross sections
- For each operator c_j, define a profile likelihood, and fit with measured $t\bar{t}W/Z$ cross sections



Operator	Best fit point(s)	1 standard deviation CL	2 standard deviation CL
$\bar{c}_{uB}$	−0.07 and 0.07	[−0.11, 0.11]	[−0.14, 0.14]
$\bar{c}_{3W}$	−0.28 and 0.28	[−0.36, −0.18] and [0.18, 0.36]	[−0.43, 0.43]
$\bar{c}'_{HQ}$	0.12	[−0.07, 0.18]	[−0.33, −0.24] and [−0.02, 0.23]
$\bar{c}_{Hu}$	−0.47 and 0.13	[−0.60, −0.23] and [−0.11, 0.26]	[−0.71, 0.37]
$\bar{c}_{HQ}$	−0.09 and 0.41	[−0.22, 0.08] and [0.24, 0.54]	[−0.31, 0.63]

Run 1 $t\bar{t}\gamma$ analysis

ATLAS 7 TeV analysis (4.59 fb^{-1})

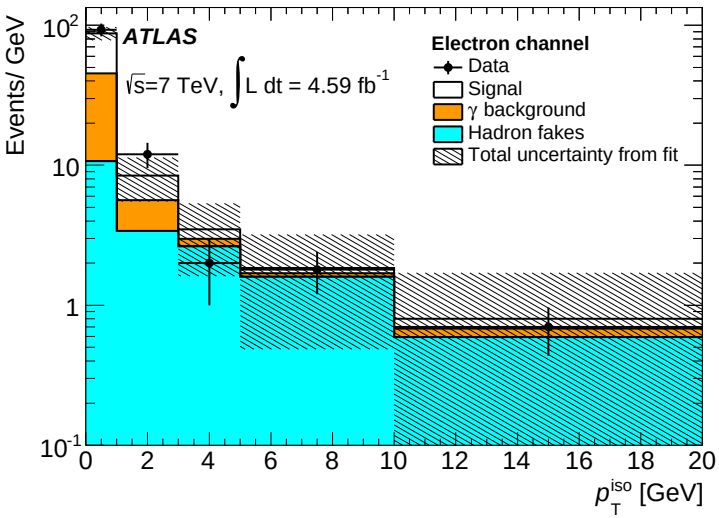
- $t\bar{t}$ events are preselected by requiring exactly one electron or muon, and at least four jets (including one b-jet)
- $t\bar{t}\gamma$ events are the subset of $t\bar{t}$ events with at least one photon of $p_T \geq 20$ GeV
- Also define fiducial phase space to be similar to the $t\bar{t}\gamma$ event selection
- $t\bar{t}\gamma$ cross section is extracted using a template-based profile likelihood fit, using photon track-isolation as discriminant

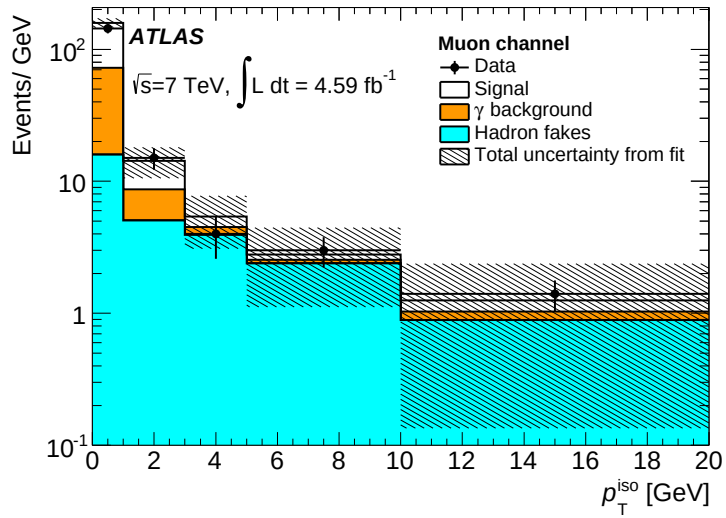
CMS 8 TeV analysis (19.7 fb^{-1})

- $t\bar{t}$ events are preselected by requiring exactly one muon, and at least four jets (including one b-jet)
- $t\bar{t}\gamma$ events are the subset of $t\bar{t}$ events with at least one photon of $p_T \geq 25$ GeV
- The number of real/fake photon events is estimated by a template-based likelihood fit, using charged hadron isolation of photon as discriminant

ATLAS Run 1 $t\bar{t}\gamma$ analysis: PRD 91 (2015) 072007

- Extract $t\bar{t}\gamma$ cross section in electron and muon channels

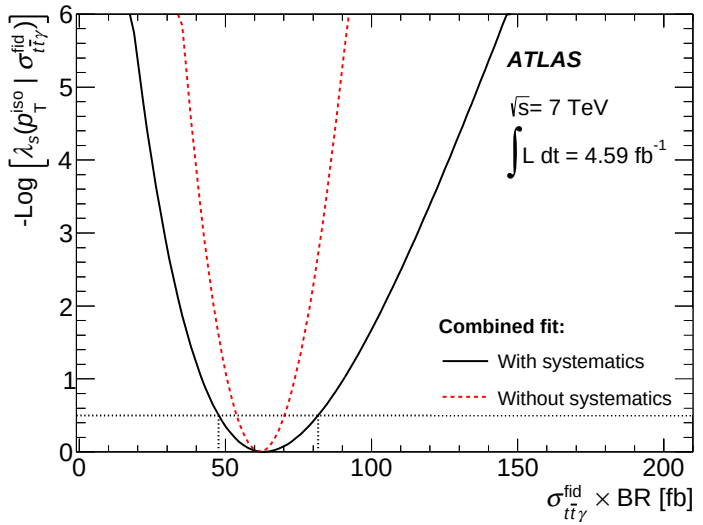




- The observed significance of $t\bar{t}\gamma$ is 5.3σ
- $\sigma^{fid}_{t\bar{t}\gamma} \times BR(t\bar{t} \to \ell j) = 63 \pm 8\,(\text{stat.})\,^{+17}_{-13}\,(\text{syst.}) \pm 1\,(\text{lumi.})\,\text{fb}$

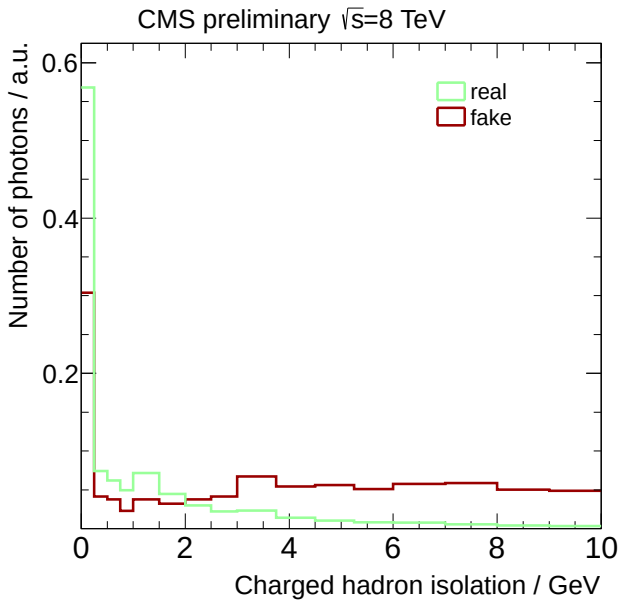
  (the NLO prediction is 48 fb)

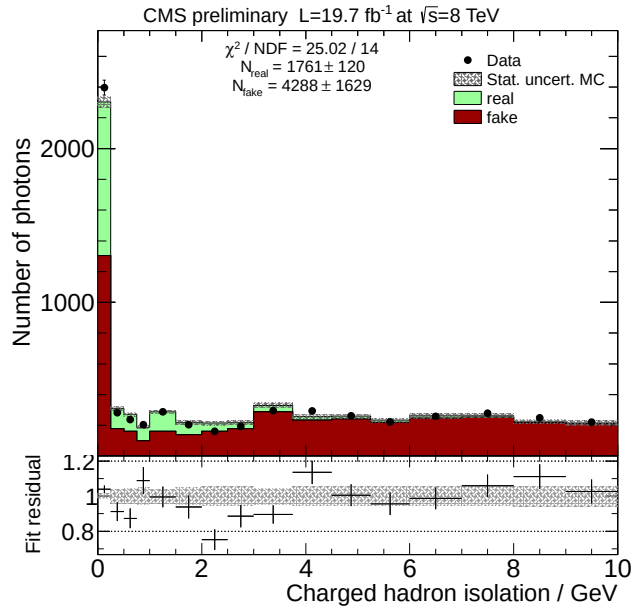
  Systematic uncertainties (jet modeling) dominate



CMS Run 1 $t\bar{t}\gamma$ analysis: CMS-PAS-TOP-13-011

- Template fit using charged hadron isolation as discriminant





- The observable $R = \sigma_{t\bar{t}\gamma}/\sigma_{t\bar{t}}$ is calculated using number of real photon events, and parameters of event selection
- $R = (1.07 \pm 0.07\,(\mathrm{stat.}) \pm 0.27\,(\mathrm{syst.})) \times 1\%$

- $t\bar{t}\gamma$ cross section is obtained from multiplying R by $\sigma_{t\bar{t}}^{CMS}$
- $\sigma_{t\bar{t}\gamma} = 2.4 \pm 0.2\,(\mathrm{stat.}) \pm 0.6\,(\mathrm{syst.})\,\mathrm{pb}$

(the NLO prediction is 1.8 pb)

Systematic uncertainties (background modeling) dominate

Run 2 $t\bar{t}V$ analyses

Preliminary:

- ATLAS 13 TeV $t\bar{t}W/Z$ analysis (ATLAS-CONF-2016-003)
- CMS 13 TeV $t\bar{t}Z$ analysis (CMS-PAS-TOP-16-009)

Run 2 $t\bar{t}W/Z$ analysis

ATLAS 13 TeV analysis (3.2 fb^{-1})

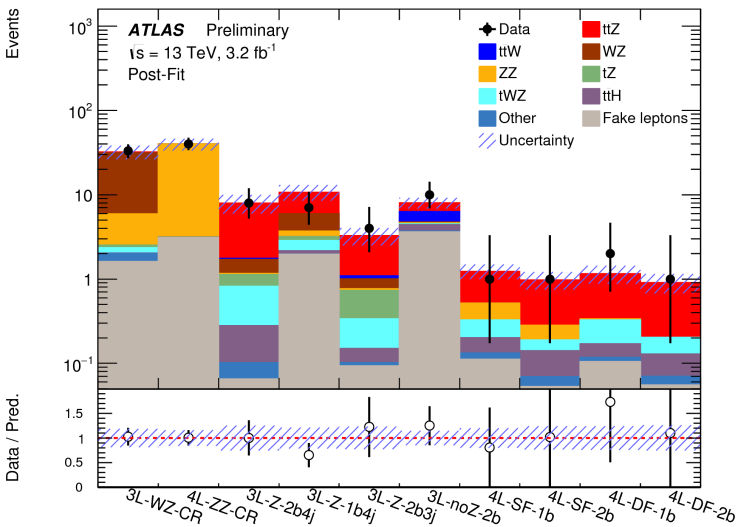
- Three final states: 2μSS, 3L, 4L
  - 2μSS: require $N_{\mathrm{bjets}} \geq 2$
  - 3L: split regions by Z/noZ, N_{jets}, N_{bjets}
  - 4L: choose the best Z candidate, split regions by N_{bjets} and relative flavour of two remaining leptons
- Control regions are defined to constrain main backgrounds: WZ (3L) and ZZ (4L)

CMS 13 TeV analysis (2.7 fb^{-1})

- Two final states: 3L, 4L
  - 3L: require exactly 1 Z candidate, split regions by N_{jets}, N_{bjets}
  - 4L: require exactly 1 Z candidate, split regions by N_{bjets}

ATLAS Run 2 $t\bar{t}W/Z$ analysis: ATLAS-CONF-2016-003

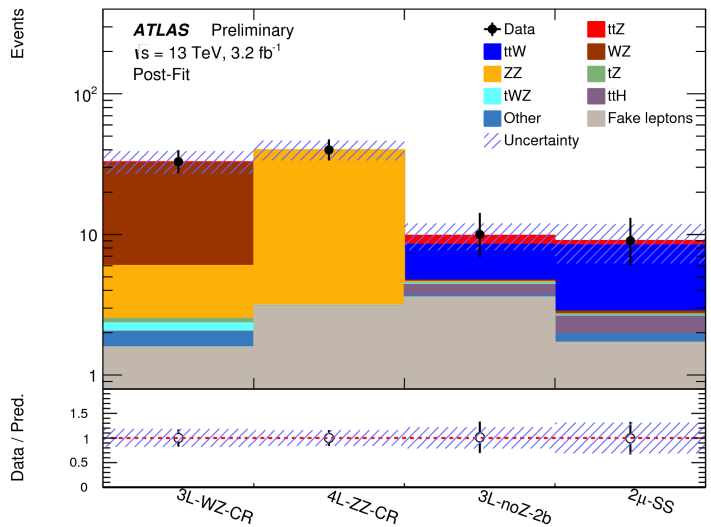
- Extract $t\bar{t}Z$ cross section using 3L-Z, 4L signal regions, and WZ, ZZ control regions



- $\sigma_{t\bar{t}Z}^{ATLAS} = 0.9 \pm 0.3\,\mathrm{pb}$

  $(\sigma_{t\bar{t}Z}^{NLO} = 0.76 \pm 0.08\,\mathrm{pb})$

- Extract $t\bar{t}W$ cross section using 2μSS, 3L-no$Z$ signal regions, and WZ, ZZ control regions



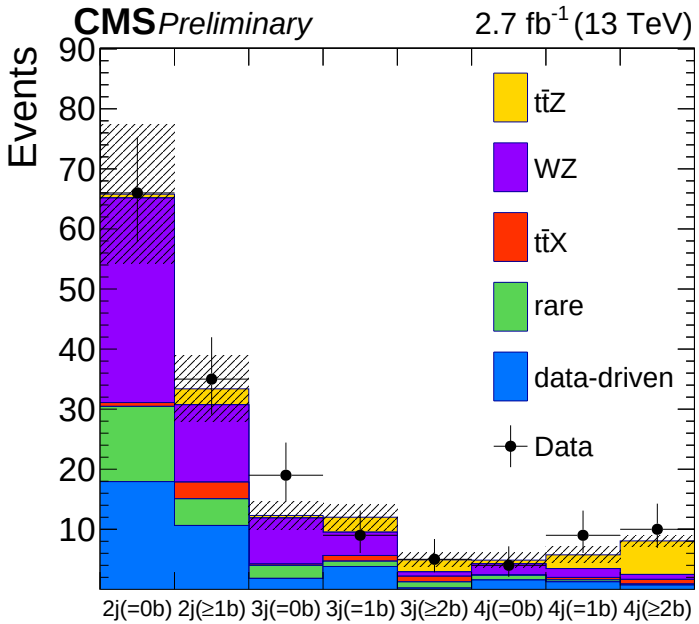
- $\sigma_{t\bar{t}W}^{ATLAS} = 1.4 \pm 0.8\,\mathrm{pb}$

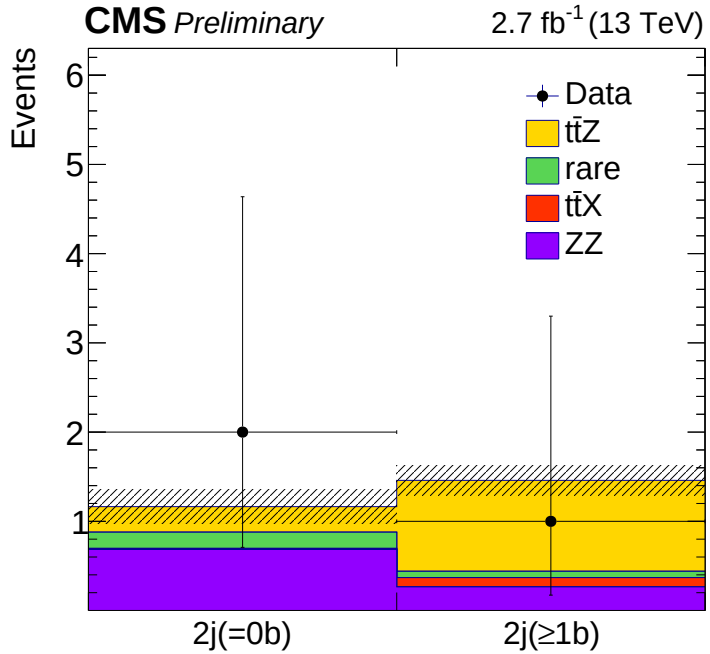
  $(\sigma_{t\bar{t}W}^{NLO} = 0.57 \pm 0.06\,\mathrm{pb})$

Statistical uncertainties dominate

CMS Run 2 $t\bar{t}Z$ analysis: CMS-PAS-TOP-16-009

- Extract $t\bar{t}Z$ cross section using 3L and 4L signal regions





- $\sigma_{t\bar{t}Z}^{CMS} = 1065^{+352}_{-313}\,(\text{stat.})^{+168}_{-142}\,(\text{syst.})\,\text{fb}$

Statistical uncertainties dominate

	Significance (σ)	
Channel	Expected	Observed
3ℓ	2.9	3.5
4ℓ	1.2	0.9
Combined	3.1	3.6

Conclusion

Run 1 $t\bar{t}V$ analyses:

- $t\bar{t}W$, $t\bar{t}Z$, and $t\bar{t}\gamma$ were all observed for the first time
- All measurements are consistent with the NLO calculations

Run 2 $t\bar{t}V$ analyses:

- Some preliminary measurements have been published
- More statistics are needed to study $t\bar{t}V$ differentially, which will be very helpful to constrain certain EFT operators (http://arxiv.org/pdf/1601.08193.pdf)