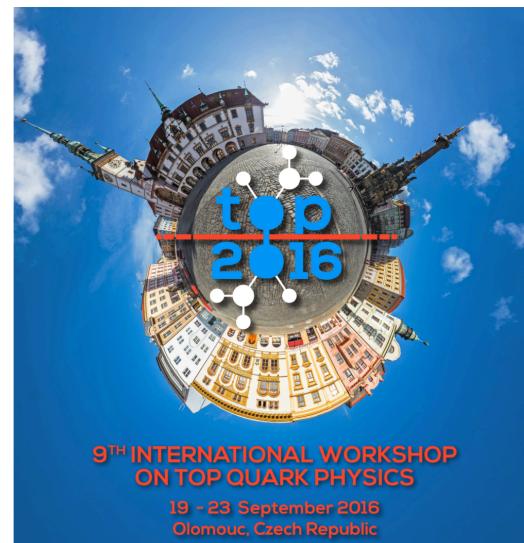
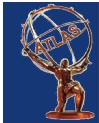


Studies of $t\bar{t}+V$ in ATLAS

María Moreno Llácer, for ATLAS collaboration

2nd Institute of Physics, Georg-August-Universität Göttingen





$t\bar{t}+\gamma$ @ 7 TeV (4.6 fb^{-1}): Phys. Rev. D 91, 072007 (2015)

→ first observation of $t\bar{t}+\gamma$, presented in TOP2015

$t\bar{t}+\gamma$ @ 8 and 13 TeV: working on it ☺

$t\bar{t}+Z/W$ @ 8 TeV (20.3 fb^{-1}): JHEP 11 (2015) 172

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$t\bar{t}+Z/W$ @ 13 TeV

→ 2015 dataset (3.2 fb^{-1})

Moriond2016 preliminary result: [ATLAS-CONF-2016-003](#)

Final (NEW) results: [arXiv:1609.01599](#) (submitted to EPJC)

→ 2016 dataset: working on it ☺

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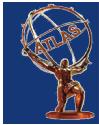
Submitted to: Eur. Phys. J. C



CERN-EP-2016-185
7th September 2016

Measurement of the $t\bar{t}Z$ and $t\bar{t}W$ production cross sections
in multilepton final states using 3.2 fb^{-1} of pp collisions
at $\sqrt{s} = 13 \text{ TeV}$ with the ATLAS detector

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In this talk, I will present $t\bar{t}+Z/W$ results at 13 TeV.

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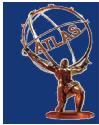
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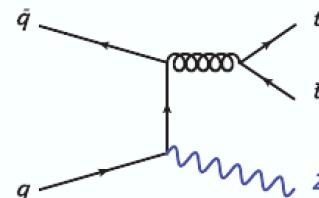
- Motivation to study $t\bar{t}Z$ and $t\bar{t}W$ processes
- Experimental signatures
- Analyses and main backgrounds
- Review ATLAS Run 1 results
- Cross section measurement at 13 TeV
 - $2\mu\mu SS$, 3l and 4l channels
 - combined fit
- Conclusions/Outlook

ttZ and ttW are rare SM processes, predicted at NLO QCD

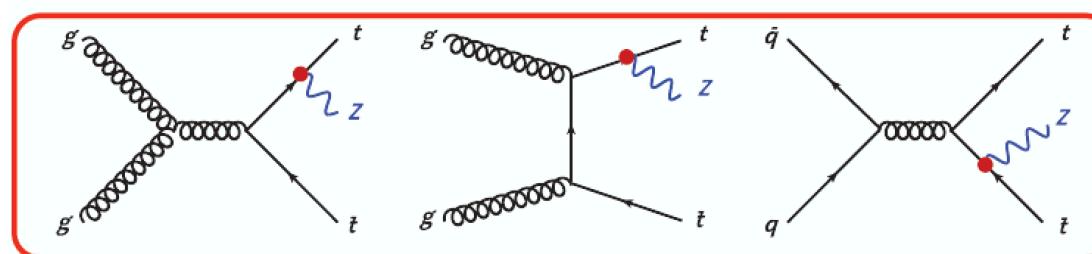
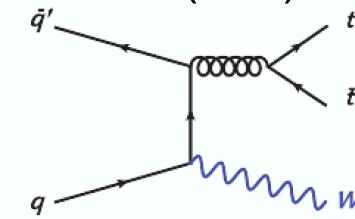
ttZ: directly sensitive to neutral current top coupling

ttW: source of same-sign leptons, sensitive to new couplings,
background for new physics searches with SS leptons

ttZ (ISR and FSR)



ttW (ISR)



$$\gamma^\mu (C_V^{SM} - \gamma_5 C_A^{SM})$$

The tZ vertex allows the measurement of weak neutral current interaction of the top quark \rightarrow weak isospin T_3

$$C_V^{SM} = T^3 - 2Q_t \sin^2(\theta_W) \quad C_A^{SM} = T^3$$

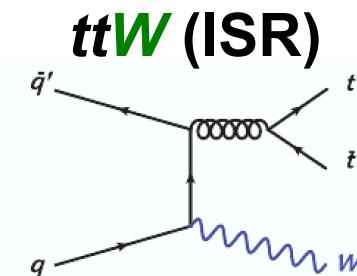
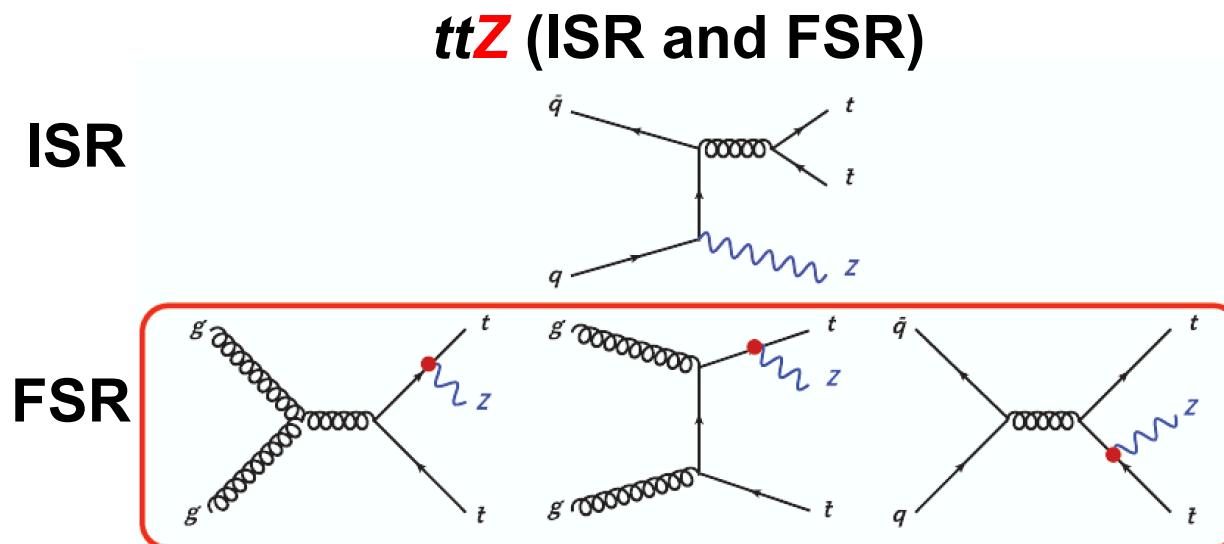
→ Cross-sections can be modified by new physics

→ Important irreducible background for ttH(multilep), VLQ, SUSY, etc.

ttZ and ttW are rare SM processes, predicted at NLO QCD

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→ Cross-sections can be modified by new physics

→ Important irreducible background for ttH(multilep), VLQ, SUSY, etc.

- Depending on decay mode of $t\bar{t}$ and Z/W: 0-4 leptons in final state

ttZ	$tt \rightarrow$ dilepton	$tt \rightarrow l+jets$	$tt \rightarrow$ all-had.
$Z \rightarrow ll$	$4l + 2j(2b)$	$3l + 4j(2b)$	$2l$ (OS) + $6j(2b)$
$Z \rightarrow \nu\nu, Z \rightarrow jj$	$2l$ (OS) + $\geq 2j(\geq 2b)$	$1l + \geq 4j(\geq 2b)$	$0l + \geq 6j(\geq 2b)$

Z decay modes:
 $BR(Z \rightarrow ee/\mu\mu/\tau\tau)$: 0.10
 $BR(Z \rightarrow \nu\nu)$: 0.20
 $BR(Z \rightarrow jj)$: 0.70

ttW	$tt \rightarrow$ dilepton	$tt \rightarrow l+jets$	$tt \rightarrow$ all-had.
$W \rightarrow l\nu$	$3l + 2j(2b)$	$2l$ (OS or SS) + $4j(2b)$	$1l + 6j(2b)$
$W \rightarrow jj$	$2l$ (OS) + $\geq 2j(\geq 2b)$	$1l + \geq 4j(\geq 2b)$	$0l + \geq 6j(\geq 2b)$

Experimental analyses focus on 2l OS or SS, 3l and 4l channels with e and/or μ .

- Channels further split according to lepton flavour/charges, # jets, etc.
 - either to disentangle ttW and ttZ or to do separate optimization to enhance signal sensitivity

Opposite-sign dilepton (2L OS)		Same-sign dilepton (2L SS)			Trilepton (3L)		Tetralepton (4L)	
different flavor (DF)	same flavor (SF)	ee	$e\mu$	$\mu\mu$	W enriched	Z enriched	DF	SF
$t\bar{t} \rightarrow \ell^\pm$ & $W \rightarrow \ell^\mp$	$t\bar{t} \rightarrow \ell^+\ell^-$ or $Z \rightarrow \ell^+\ell^-$	$t\bar{t} \rightarrow \ell^\pm$ & $W \rightarrow \ell^\pm$	$t\bar{t} \rightarrow \ell^+\ell^-$	$t\bar{t} \rightarrow \ell$	$Z \rightarrow \ell^+\ell^-$	$Z \rightarrow \ell^+\ell^-$	$t\bar{t} \rightarrow DF$	$t\bar{t} \rightarrow SF$

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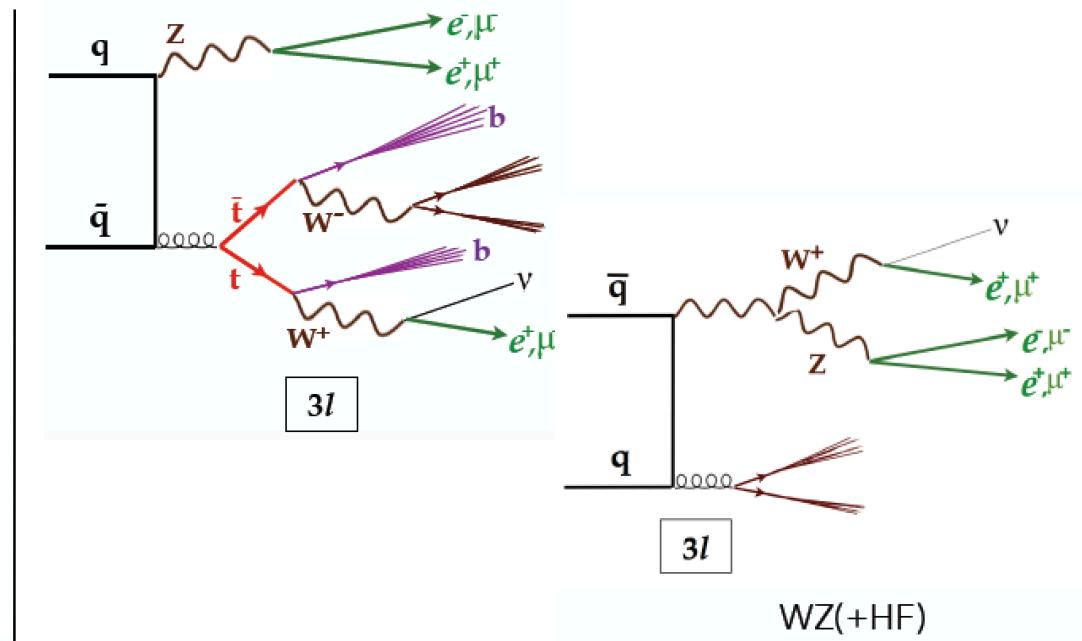
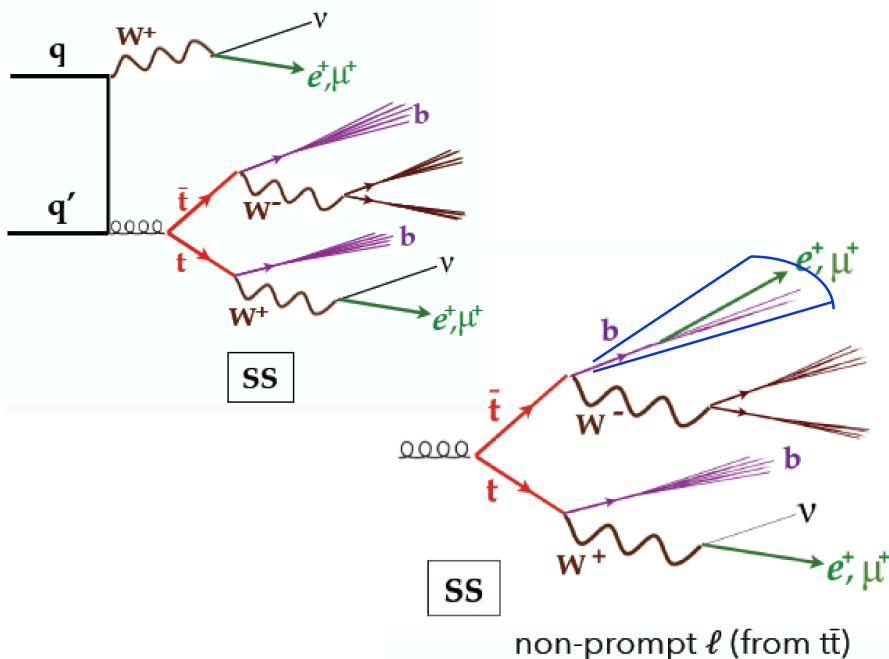
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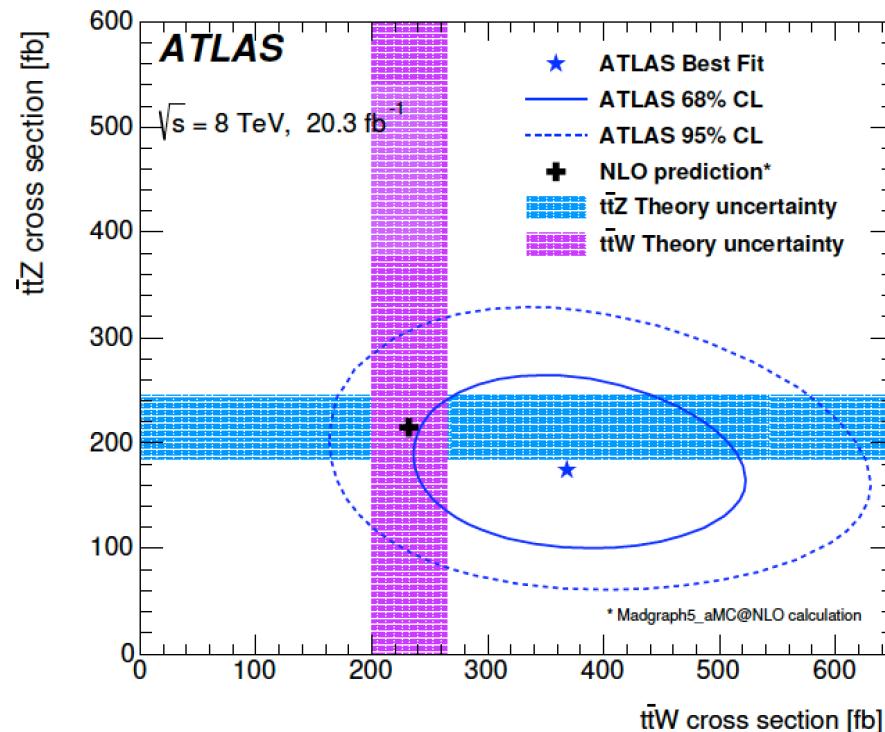
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different flavor (DF)	same flavor (SF)	ee	$e\mu$	$\mu\mu$	W enriched	Z enriched	DF	SF
$t\bar{t} \rightarrow \ell^\pm$ & $W \rightarrow \ell^\mp$	$t\bar{t} \rightarrow \ell^+\ell^-$ or $Z \rightarrow \ell^+\ell^-$	$t\bar{t} \rightarrow \ell^\pm$ & $W \rightarrow \ell^\pm$	$t\bar{t} \rightarrow \ell^+\ell^-$	$t\bar{t} \rightarrow \ell$	$Z \rightarrow \ell^+\ell^-$	$Z \rightarrow \ell^+\ell^-$	$t\bar{t} \rightarrow DF$	$t\bar{t} \rightarrow SF$

- Sample statistics, S/B ratio and dominant backgrounds vary across different channels

Channel	Sub-channels	Characteristics	Main cuts	Main background
OS dilepton	diff. (same) flavour	small S/B	≥ 3 jets, ≥ 1 b-tag	tt (Z) dileptonic decay
SS dilepton	ee, e μ ($\mu\mu$)	targets ttW	≥ 2 b-tags	charge mis-ID (fake leptons)
Trilepton	ttZ (ttW) enriched	small sample size, good S/B	≥ 1 b-tag	leptonic decay WZ, rare SM (fake leptons)
Tetralepton	tt \rightarrow same (diff.) flavour	very small sample size, excellent S/B	1-2 OSSF pairs	leptonic decay ZZ (rare SM)



$t\bar{t}+Z/W$ ATLAS Run 1 results



$$\sigma(t\bar{t}Z) = 176^{+52}_{-48}(\text{stat}) \pm 24(\text{syst}) \text{ fb}$$

$$\sigma(t\bar{t}W) = 369^{+86}_{-79} (\text{stat}) \pm 44(\text{syst}) \text{ fb}$$

Uncertainty	$\sigma_{t\bar{t}W}$	$\sigma_{t\bar{t}Z}$
Luminosity	3.2%	4.6%
Reconstructed objects	3.7%	7.4%
Backgrounds from simulation	5.8%	8.0%
Fake leptons and charge misID	7.5%	3.0%
Signal modelling	1.8%	4.5%
Total systematic	12%	13%
Statistical	+24% / -21%	+30% / -27%
Total	+27% / -24%	+33% / -29%

- Statistical uncertainty dominates.
→ Main systematic uncertainty source: modelling of backgrounds.

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

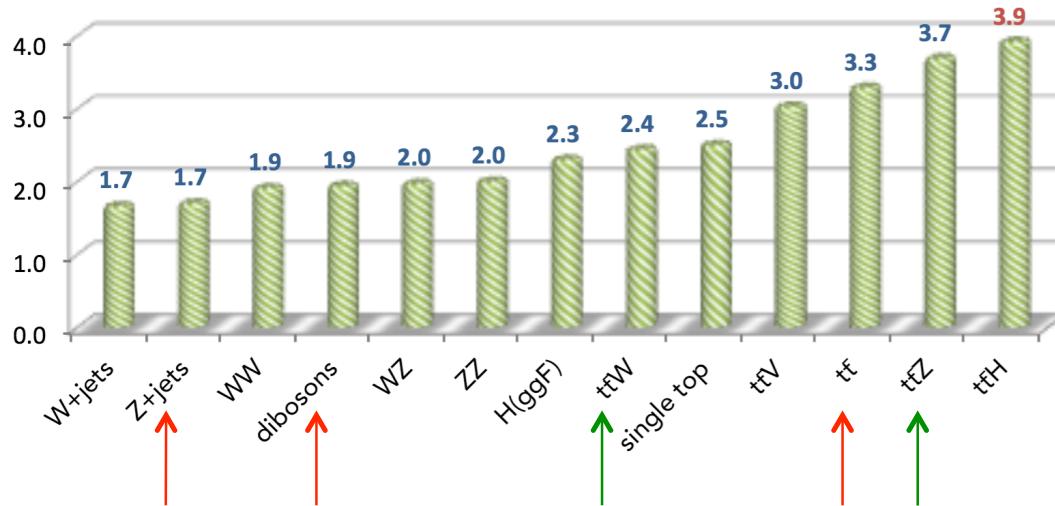


Channels	Significance	
	Expected	Observed
SS	3.4	4.9
3 ℓ	1.0	1.0
SS + 3 ℓ	3.5	4.8

Channels	Significance	
	Expected	Observed
OS	1.8	2.1
3 ℓ	4.6	5.1
4 ℓ	2.7	3.4
OS + 3 ℓ + 4 ℓ	5.7	6.4

→ First observation of $t\bar{t}+V$ processes (ATLAS & CMS with 8 TeV data)

Cross section ratios 13 TeV / 8 TeV



σ (pb)	8 TeV	13 TeV	13 / 8
ttZ	0.206 ¹ 0.215 ²	0.839 ($\pm 12\%$) ⁵	3.7
ttW	0.232 ³ 0.203 ⁴	0.601 ($\pm 13\%$) ⁵	2.4 2.8
ttH	0.129	0.5085	3.9
tt	~ 250 pb	~ 830	3.3

¹ttZ on-shell

⁵from Higgs Yellow

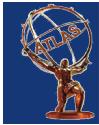
²tt+ll (on+off shell)

 Report 4, $\mu = m_t + m_V/2$
³ $\mu = m_t + m_W/2$ (ATLAS)

⁴ $\mu = m_t$ (CMS)

Channel	$t\bar{t}W$ significance		$t\bar{t}Z$ significance	
	Expected	Observed	Expected	Observed
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3 ℓ	1.4	1.0	3.7	3.3
4 ℓ	-	-	2.0	2.4
Combined	3.2	5.0	4.5	4.2

- First 13 TeV results (2015 data, 3.2 fb^{-1})
- Check of SM in new energy regime
- Similar to 8 TeV analysis
- Only the most sensitive channels used

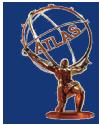


SS	1 b-tag	≥ 2 b-tags
No $E_{T,\text{miss}}$ cut		2SS-VR
$E_{T,\text{miss}}$ cut		2SS-SR

$3\ell\text{-no}Z$	1 b-tag	≥ 2 b-tags
2 jets		
3 jets		$3\ell\text{-no}Z\text{-VR}$
4 jets		

$3\ell\text{-Z}$	0 b-tag	1 b-tag	≥ 2 b-tags
2 jets			$3\ell\text{-Z-VR}$
3 jets	$3\ell\text{-WZ-CR}$		$3\ell\text{-Z-2b3j}$
≥ 4 jets		$3\ell\text{-Z-1b4j}$	$3\ell\text{-Z-2b4j}$

4ℓ	SF	DF
≥ 0 b-tags low $E_{T,\text{miss}}$ Z window	$4\ell\text{-ZZ-CR}$	
1 b-tag	$4\ell\text{-SF-1b}$	$4\ell\text{-DF-1b}$
≥ 2 b-tags	$4\ell\text{-SF-2b}$	$4\ell\text{-DF-2b}$



Consider 3 channels according to # of leptons

Define signal regions (SRs) for the 3 channels

- depending on the number of jets and b -jets

Define two control regions (CRs)
to extract WZ and ZZ normalisations

Define validation regions (VRs)
to check fake lepton estimate (not included in the fit)

Combined profile likelihood fit to SRs & CRs

- cut-and-count analysis
- extract $\mu(t\bar{t}Z)$, $\mu(t\bar{t}W)$,
and WZ and ZZ normalisation factors

2 μ SS	1 b-tag	≥ 2 b-tags
No $E_{T,\text{miss}}$ cut		2 μ SS-VR
$E_{T,\text{miss}}$ cut		2 μ SS-SR

3 ℓ -Z	0 b-tag	1 b-tag	≥ 2 b-tags
2 jets			3 ℓ -Z-VR
3 jets	3 ℓ -WZ-CR		3 ℓ -Z-2b3j
≥ 4 jets		3 ℓ -Z-1b4j	3 ℓ -Z-2b4j

3 ℓ -noZ	1 b-tag	≥ 2 b-tags
2 jets	3 ℓ -noZ-VR	
3 jets		3 ℓ -noZ-2b
4 jets		

4 ℓ	SF	DF
≥ 0 b-tags low $E_{T,\text{miss}}$ Z window	4 ℓ -ZZ-CR	
1 b-tag	4 ℓ -SF-1b	4 ℓ -DF-1b
≥ 2 b-tags	4 ℓ -SF-2b	4 ℓ -DF-2b

The reconstruction of $t\bar{t}+V$ final state objects (electrons, muons, jets, b -tagging and $E_{T,\text{miss}}$) requires information from all the ATLAS subdetectors
 → A proper/precise understanding of the detector (and pile-up conditions) is required.

Single electron and muon triggers

Electrons / Muons

$p_T > 7 \text{ GeV}$, $|\eta| < 2.47 / 2.4$

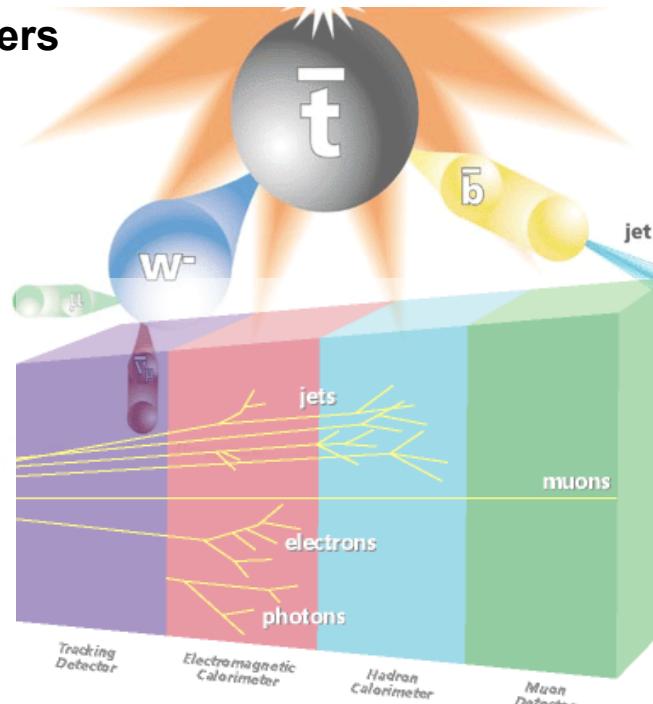
ID: LH-based / combined

IP cuts: $|d_0|/\sigma(d_0) < 5 / 3$

$|z_0 \sin\theta| < 0.5 \text{ mm}$

Isolation:

- Track: $p_{T,\text{rel}} < 0.06$ in cone of size $\min(10\text{GeV}, r_{e,\mu})$ with $r_{e,\mu} = 0.2, 0.3$
- Calo: $E_{T,\text{rel}} < 0.06$ in cone $r_e = 0.2$



Jets

Anti- k_t $R=0.4$,
 $p_T > 25 \text{ GeV}$, $|\eta| < 2.5$
 pile-up rejection criteria

b-jets

MV2c20, 77% eff. WP
 light/c-jet rejection: 130/4.5

Missing transverse energy

Overlap removal

- Electrons sharing a track with a muon are removed
- Closest jet within $\Delta R < 0.2$ of an electron is removed
- If nearest jet within $\Delta R < 0.4$, electron is discarded
- Muon removed if nearest jet within $\Delta R < 0.4$
- if jet has < 3 tracks then jet is removed and muon is kept

- Sensitive to ttW
- Signature: 2l $\mu\mu$, 4 jets (2 from *b*-quarks)
- Main background: fake leptons (from ttbar)

estimated from data-driven technique: **matrix method**

- define control region with looser lepton requirements to derive real and fake lepton efficiencies as function of the electron/muon p_T
- select dileptonic (ee, $\mu\mu$ and e μ) events with OS or SS
- classify events into N_{TT} , N_{TL} , N_{LT} , N_{LL}
- build likelihood functions
- poissonian constraints on observed N_{ij}

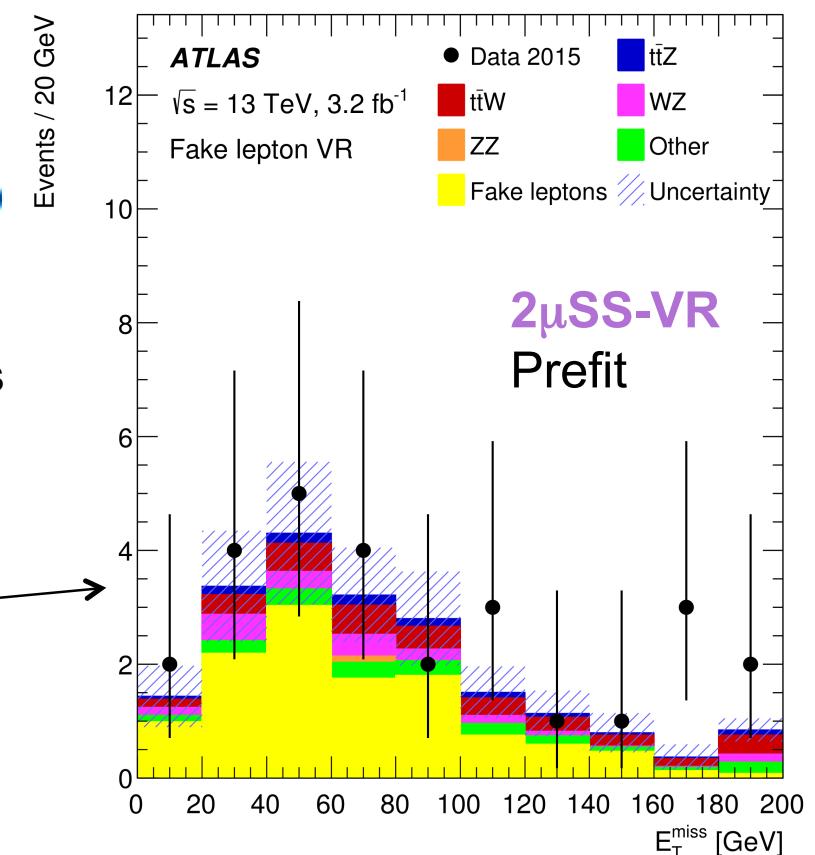
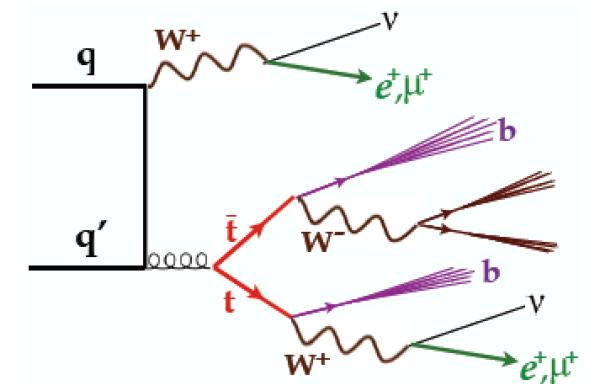
$$L = \prod_{ij} \prod_m Po(N_{ij}^m | M_{ij}^{mn}(r_i, f_i, r_j, f_j) n_{ij}^n)$$

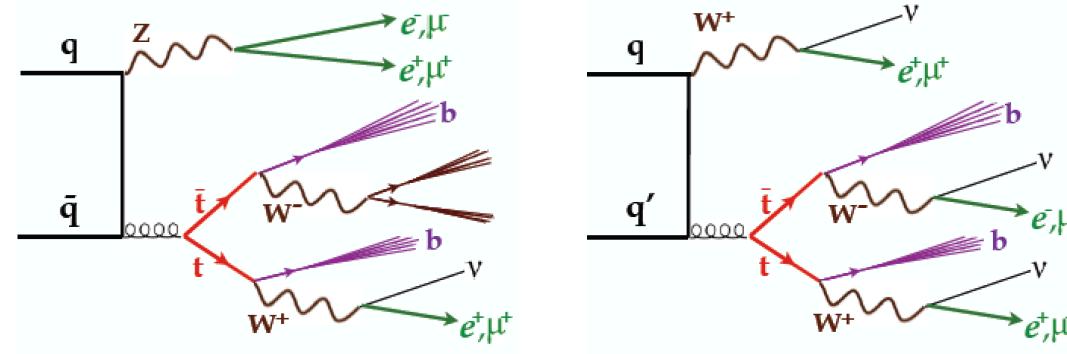
• Event selection

same sign $\mu\mu$ pair with $p_T > 25$ GeV, veto add. leptons
 ≥ 2 b-jets, $E_{T,\text{miss}} > 40$ GeV, $H_T(\text{leptons+jets}) > 140$ GeV

2 μ SS	1 b-tag	≥ 2 b-tags
No $E_{T,\text{miss}}$ cut	2 μ SS-VR	
$E_{T,\text{miss}}$ cut	2 μ SS-SR	

- Validation region for fakes with relaxed cuts:
 $p_T^{2\text{nd}} > 20$ GeV, ≥ 1 b-tagged jet, no MET requirement





3ℓ -Z	0 b-tag	1 b-tag	≥ 2 b-tags
2 jets			
3 jets	3ℓ-WZ-CR	3ℓ-Z-VR	3ℓ-Z-2b3j
≥ 4 jets		3ℓ-Z-1b4j	3ℓ-Z-2b4j

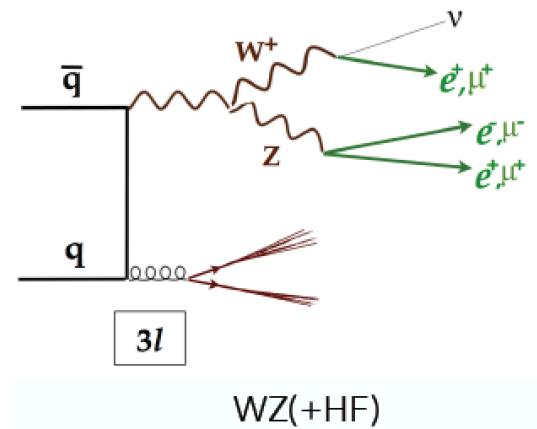
- Four signal regions: three sensitive to ttZ and one to ttW

Variable	3 ℓ -Z-1b4j	3 ℓ -Z-2b3j	3 ℓ -Z-2b4j	3 ℓ -noZ-2b	3 ℓ -noZ	1 b-tag	≥ 2 b-tags
Leading lepton				$p_T > 25 GeV$	2 jets		
Other leptons				$p_T > 20 GeV$	3 jets	3ℓ-noZ-VR	
Sum of lepton charges				± 1	4 jets		
Z-like OSSF pair		$ m_{\ell\ell} - m_Z < 10 GeV$		$ m_{\ell\ell} - m_Z > 10 GeV$			
n_{jets}	≥ 4	3	≥ 4	≥ 2 and ≤ 4			
$n_{b-\text{jets}}$	1	≥ 2	≥ 2	≥ 2			

• Control region for WZ

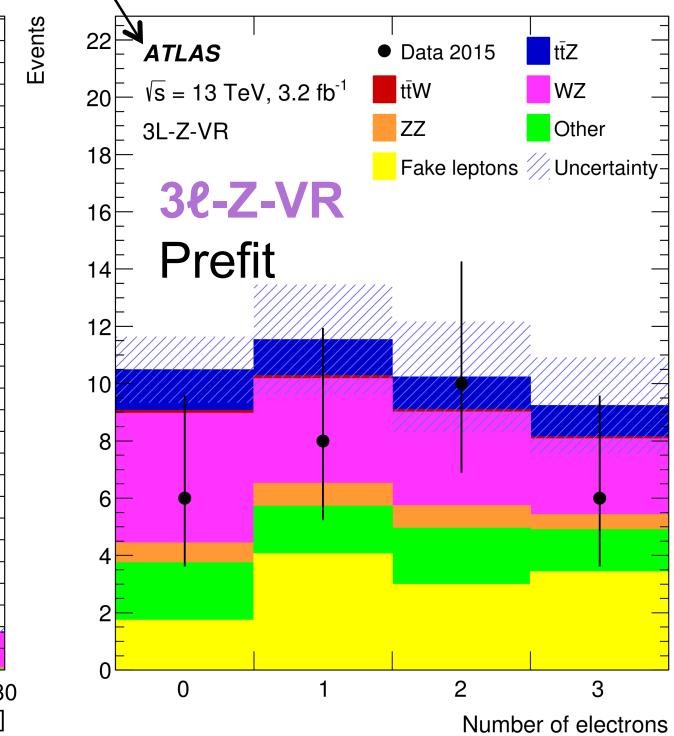
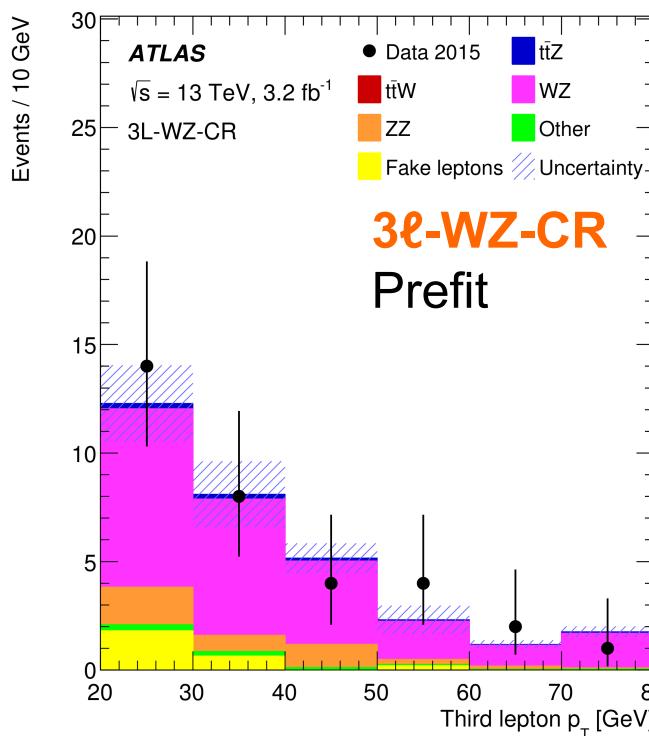
WZ+jets CR with 0 b-jets (**3 ℓ -WZ-CR**) and prompt leptons in order to check that 3l WZ events are described by MC

- Validation regions for fakes (from ttbar and Z+jets): **3 ℓ -Z-VR** and **3 ℓ -noZ-VR**

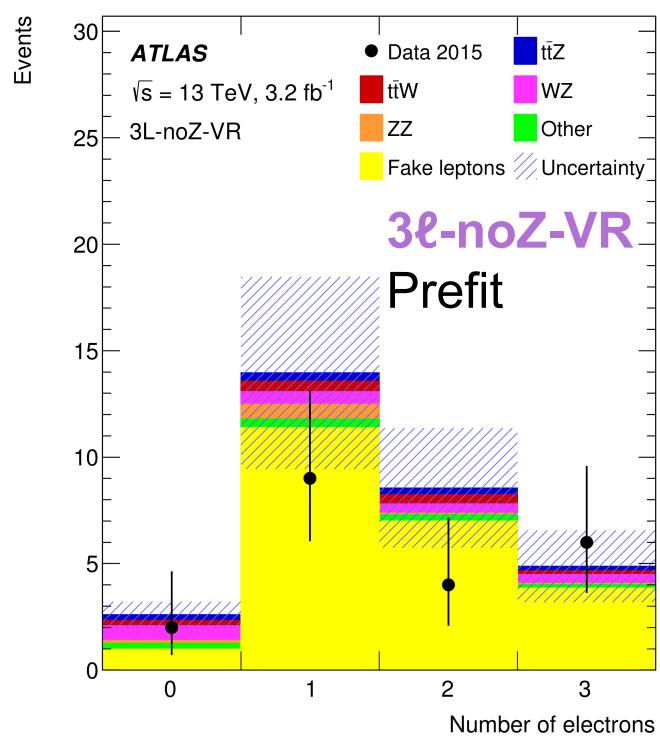


3l: control and validation regions

3ℓ-Z	0 b-tag	1 b-tag	≥2 b-tags
2 jets			<i>3ℓ-Z-VR</i>
3 jets	3ℓ-WZ-CR	<i>3ℓ-Z-VR</i>	3ℓ-Z-2b3j
≥4 jets		3ℓ-Z-1b4j	3ℓ-Z-2b4j



3ℓ-noZ	1 b-tag	≥2 b-tags
2 jets		
3 jets		<i>3ℓ-noZ-VR</i>
≥4 jets		3ℓ-noZ-2b

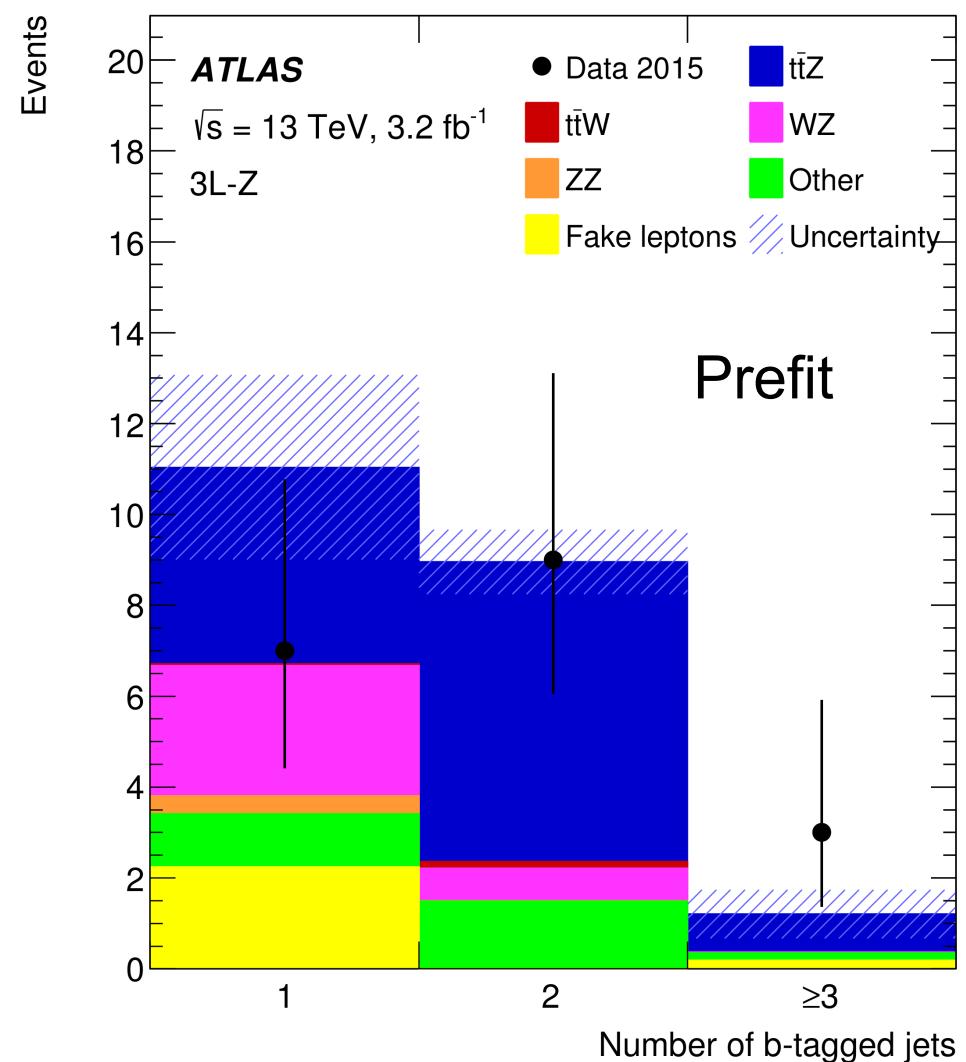
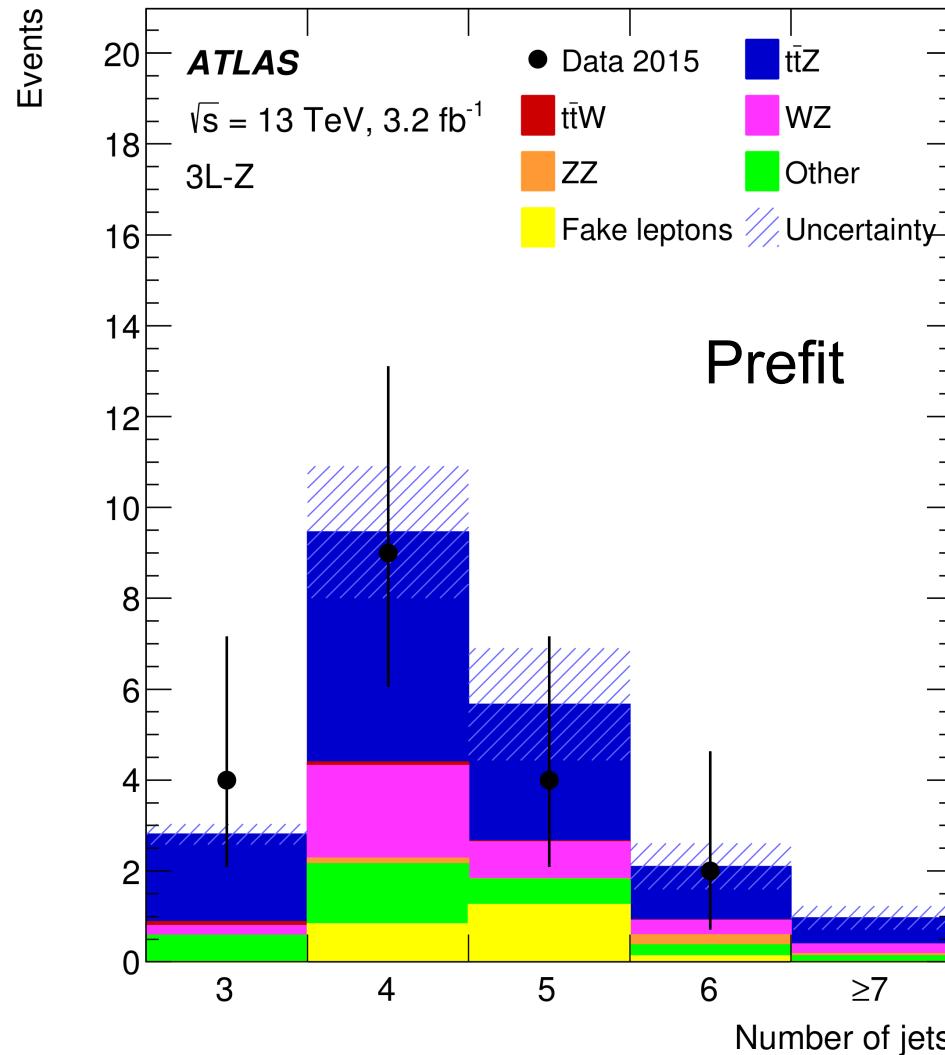


→ CR to constrain WZ normalisation.

→ Data and background prediction are in good agreement.

3l signal regions sensitive to ttZ (19 events observed)

Signal normalised to SM expectation



- Smallest branching ratio, high purity
- Main background: diboson (ZZ), Higgs, fake leptons ($t\bar{t}$ bar and $Z+jets$)

from MC and corrected
with factors derived
in dedicated CR

• Four signal regions

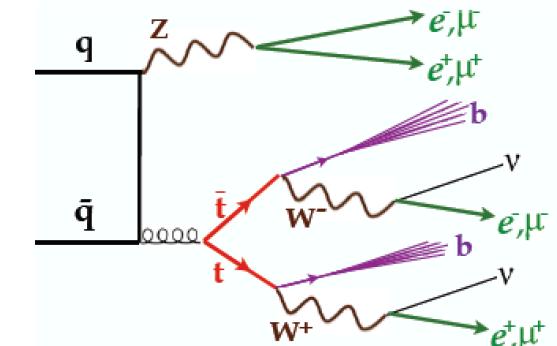
4 leptons $\rightarrow 2$ OS lepton pairs (being at least 1 pair OSSF named Z_1)

Remaining pair (from $t\bar{t}$ bar) might be SF or DF \rightarrow define Z_2 leptons

$p_T^{1st} > 25$ GeV, $m(Z_1), m(Z_2) > 10$ GeV

4 SRs: depending on Z_2 leptons flavour and # b -jets

$p_{T,34}$ ($= p_{T,3} + p_{T,4}$) cuts in 1 b -tag regions

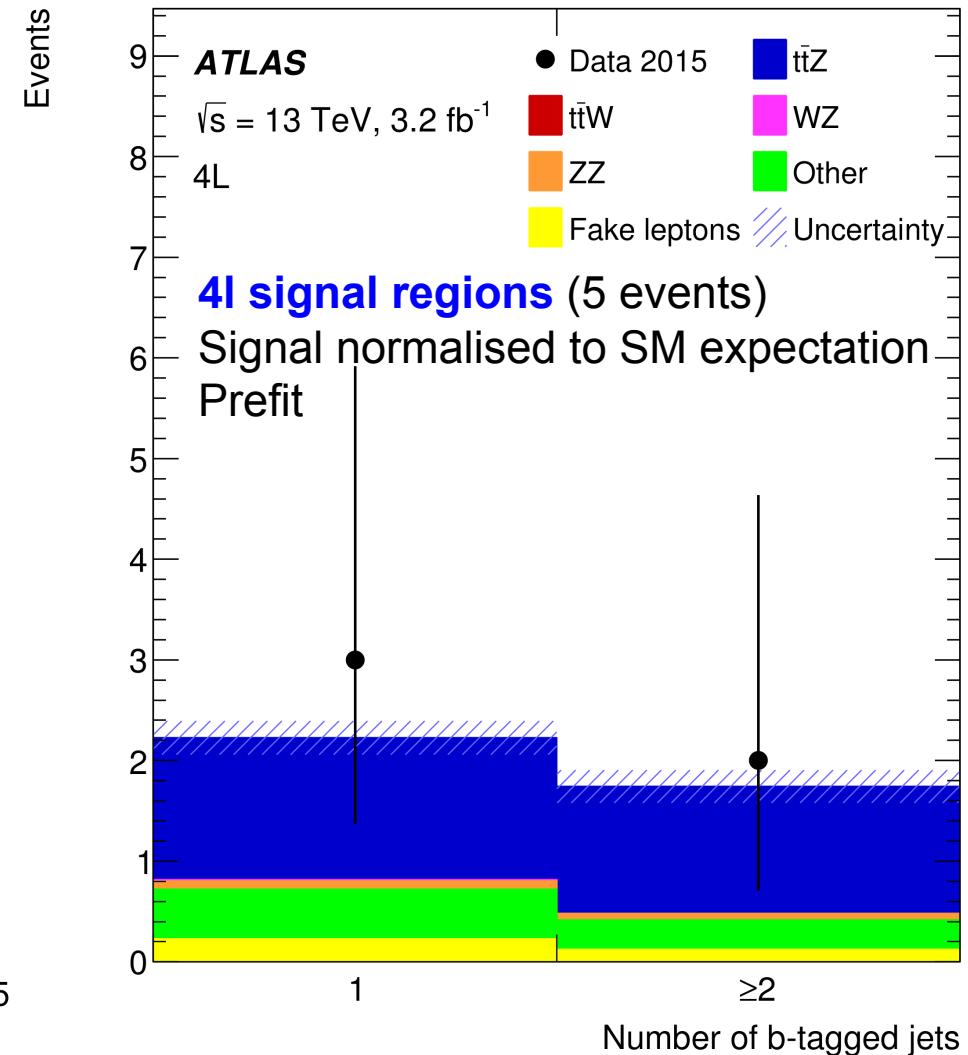
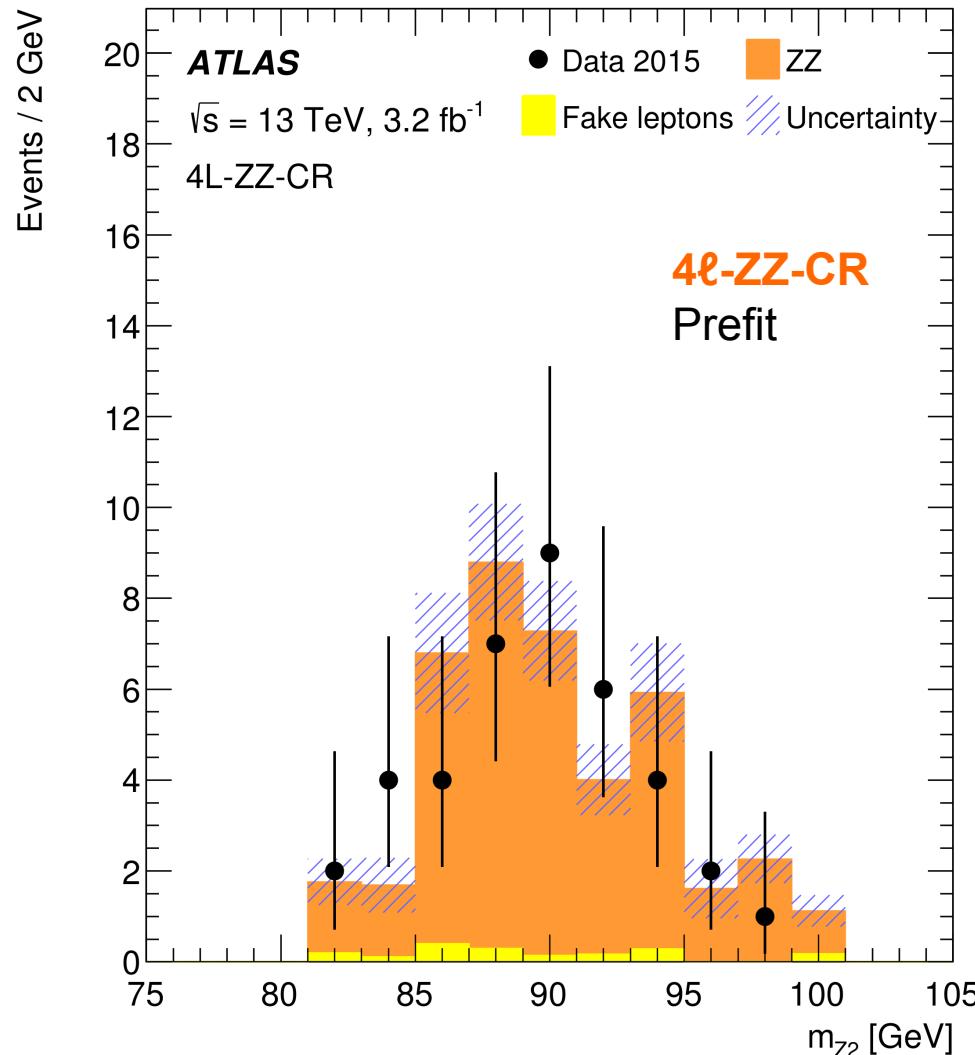


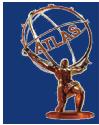
Region	Z_2 leptons	p_{T34}	$ m_{Z_2} - m_Z $	E_T^{miss}	$N_{b\text{-jets}}$
$4\ell\text{-DF-1b}$	$e^\pm\mu^\mp$	> 35 GeV	-	-	1
$4\ell\text{-DF-2b}$	$e^\pm\mu^\mp$	-	-	-	≥ 2
$4\ell\text{-SF-1b}$	$e^\pm e^\mp, \mu^\pm \mu^\mp$	> 25 GeV	$\begin{cases} > 10 \text{ GeV} \\ < 10 \text{ GeV} \end{cases}$	$\begin{cases} > 40 \text{ GeV} \\ > 80 \text{ GeV} \end{cases}$	1
$4\ell\text{-SF-2b}$	$e^\pm e^\mp, \mu^\pm \mu^\mp$	-	$\begin{cases} > 10 \text{ GeV} \\ < 10 \text{ GeV} \end{cases}$	$\begin{cases} - \\ > 40 \text{ GeV} \end{cases}$	≥ 2

4ℓ	SF	DF
≥ 0 b-tags low $E_{T,\text{miss}}$ Z window	$4\ell\text{-ZZ-CR}$	
1 b-tag	$4\ell\text{-SF-1b}$	$4\ell\text{-DF-1b}$
≥ 2 b-tags	$4\ell\text{-SF-2b}$	$4\ell\text{-DF-2b}$

• Control region for ZZ (**$4\ell\text{-ZZ-CR}$**)

Two OSSF lepton pairs with $|m_{Z_1} - m_Z| < 10$ GeV and $|m_{Z_2} - m_Z| < 10$ GeV, and $E_{T,\text{miss}} < 40$ GeV





Simultaneous binned profile likelihood fit $L(\mu, \theta)$ to all analysis regions (S+B hypothesis)

$$L(\mu, \theta) = L_{Pois}(\mu, \theta) \cdot \prod_p \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{\theta_p^2}{2}\right)$$

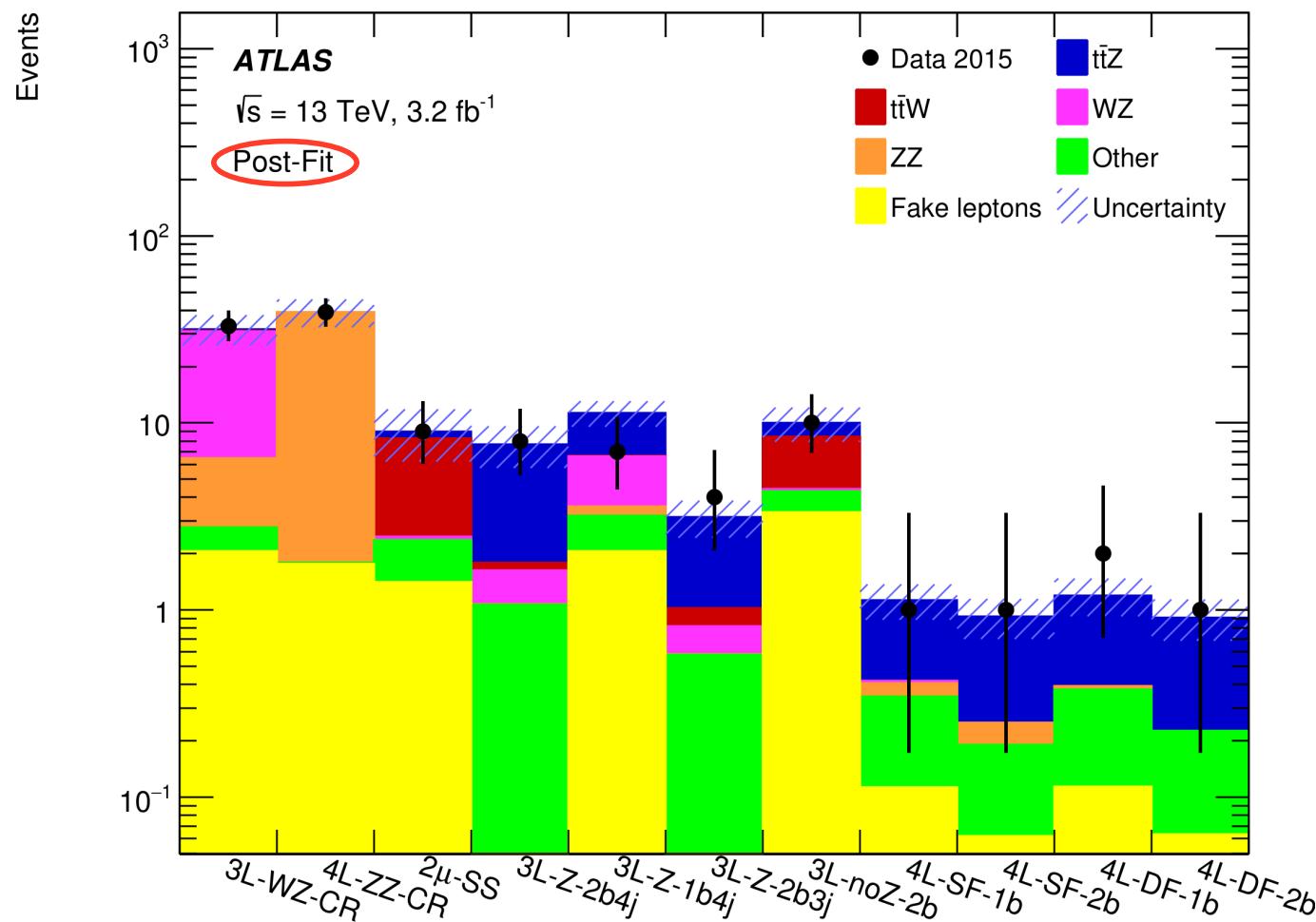
$$\downarrow$$
$$L_{Pois}(\mu) = \prod_j^{reg} \prod_i^{bins(j)} \frac{(\mu s_{ij} + b_{ij})^{n_{ij}}}{n_{ij}!} \exp(-(\mu s_{ij} + b_{ij})) \quad \text{with} \quad \mu = \frac{\sigma_{t\bar{t}V}}{\sigma_{t\bar{t}V}^{SM}}$$

- parameter of interest: signal strength $\mu_{t\bar{t}Z}$ and $\mu_{t\bar{t}W}$
- nuisance parameters θ_p : systematic uncertainties
- include CRs to constrain WZ and ZZ backgrounds (floating normalisation factors correlated across ch.)

Jets: includes unc. related to pile-up rejection criteria (JVT), **dominant**

Fakes derived using matrix-method:
large uncertainties

Uncertainty	$\sigma_{t\bar{t}Z}$	$\sigma_{t\bar{t}W}$
Luminosity 2015 data (unc. 2.5%)	2.6%	3.1%
Reconstructed objects	8.3%	9.3%
Backgrounds from simulation	5.3%	3.1%
Fake leptons and charge misID	3.0%	21%
Total systematic	11%	22%
Statistical	31%	48%
Total	32%	53%


ttZ and ttW simultaneous cross section measurement (9 SRs + 2CRs)

 WZ_norm 1.11 ± 0.30

 ZZ_norm 0.94 ± 0.17
 $\mu(\text{ttZ}) = 1.10 \pm 0.37$
 $\mu(\text{ttW}) = 2.49 \pm 1.32$

$$\sigma(\text{ttZ}) = 0.92 \pm 0.29 \text{ (stat)} \pm 0.10 \text{ (syst)} \text{ pb}$$

$$\sigma(\text{ttW}) = 1.50 \pm 0.72 \text{ (stat)} \pm 0.33 \text{ (syst)} \text{ pb}$$

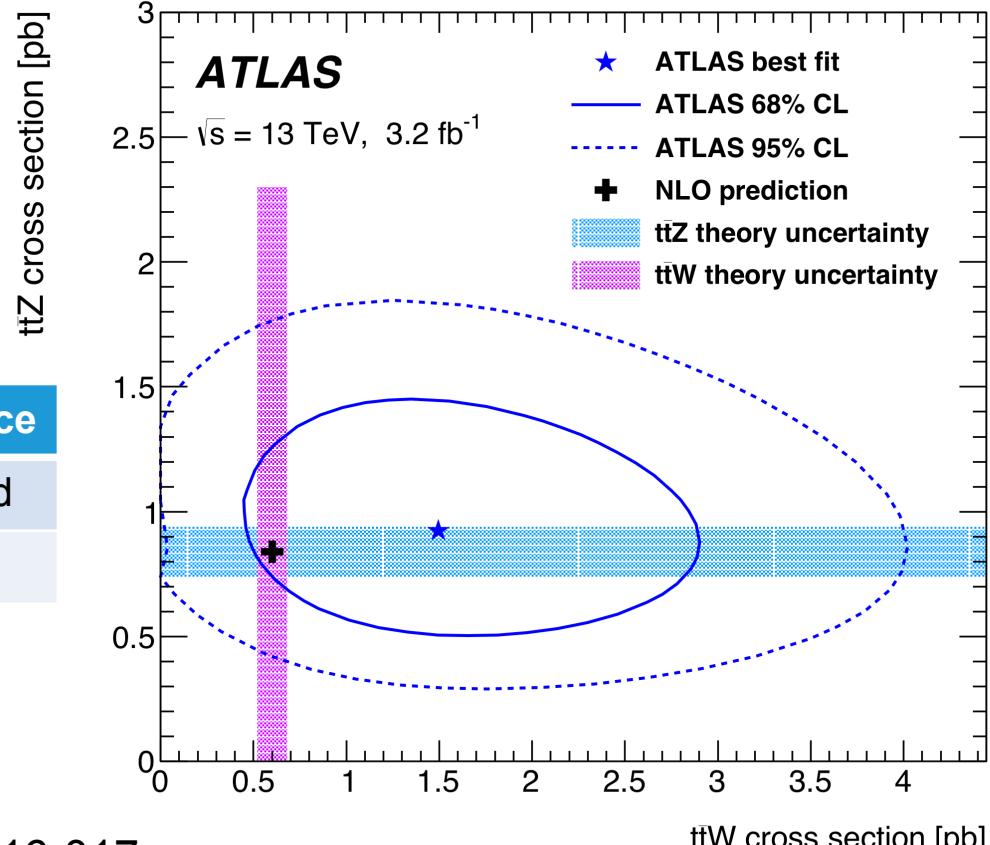
Cross section measurement

ATLAS, 2015 data, 3.2 fb^{-1}

$$\begin{aligned}\sigma(\text{ttZ}) &= 0.92 \pm 0.29 \text{ (stat)} \pm 0.10 \text{ (syst)} \text{ pb} \\ \sigma(\text{ttW}) &= 1.50 \pm 0.72 \text{ (stat)} \pm 0.33 \text{ (syst)} \text{ pb}\end{aligned}$$

ttZ signal significance		ttW signal significance	
Expected	Observed	Expected	Observed
3.4	3.9	1.0	2.2

* using asymptotic formulae

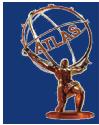


CMS, 2016 data, 12.9 fb^{-1} , CMS PAS TOP-16-017

$$\begin{aligned}\sigma(\text{ttZ}) &= 0.70^{+0.16}_{-0.15} \text{ (stat)}^{+0.14}_{-0.12} \text{ (syst)} \text{ pb} \\ \sigma(\text{ttW}) &= 0.98^{+0.23}_{-0.22} \text{ (stat)}^{+0.22}_{-0.18} \text{ (syst)} \text{ pb}\end{aligned}$$

Channel	Expected significance	Observed significance
$2\ell ss$ analysis ($t\bar{t}W$)	2.6	3.9
3ℓ analysis ($t\bar{t}Z$)	5.4	3.8
4ℓ analysis ($t\bar{t}Z$)	2.4	2.8
3ℓ and 4ℓ combined ($t\bar{t}Z$)	5.8	4.6

SM predictions (Higgs Yellow Report 4):
 $\sigma(\text{ttZ}) = 0.839 (+-12\%) \text{ pb}$
 $\sigma(\text{ttW}) = 0.600 (+-13\%) \text{ pb}$

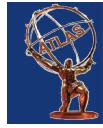


- Measurement of tt+X (X= W/Z) cross-section allows probing t-Z couplings
- **New measurement of ttZ and ttW cross-sections at 13 TeV using 2015 ATLAS dataset** has been presented
 - The results are very similar to the preliminary ones released for Moriond 2016
 - Fake lepton estimation important piece:
 - data-driven (matrix method) or correcting simulation (fake factors)
 - validated in different regions
 - Result dominated by statistical uncertainty and are compatible with SM prediction

$$\sigma(\text{ttZ}) = 0.92 \pm 0.29 \text{ (stat)} \pm 0.10 \text{ (syst)} \text{ pb}$$

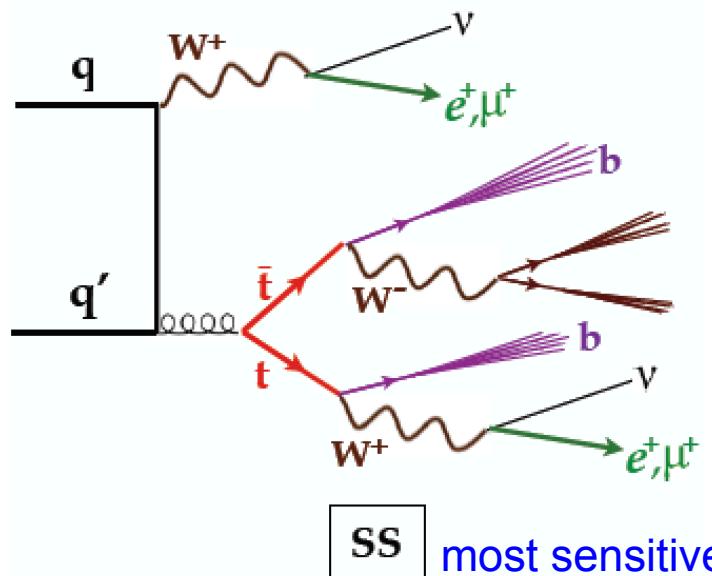
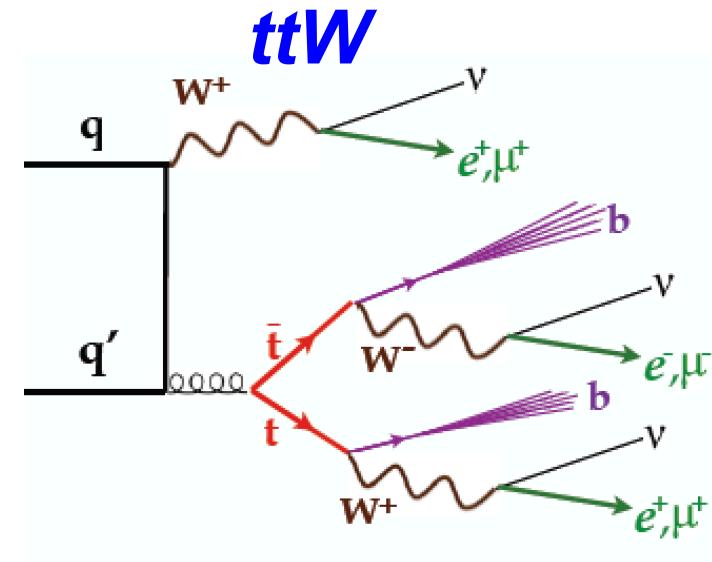
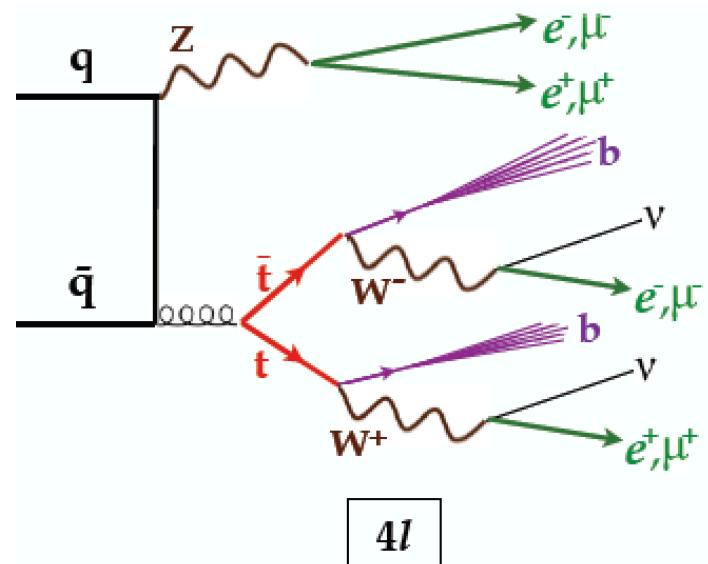
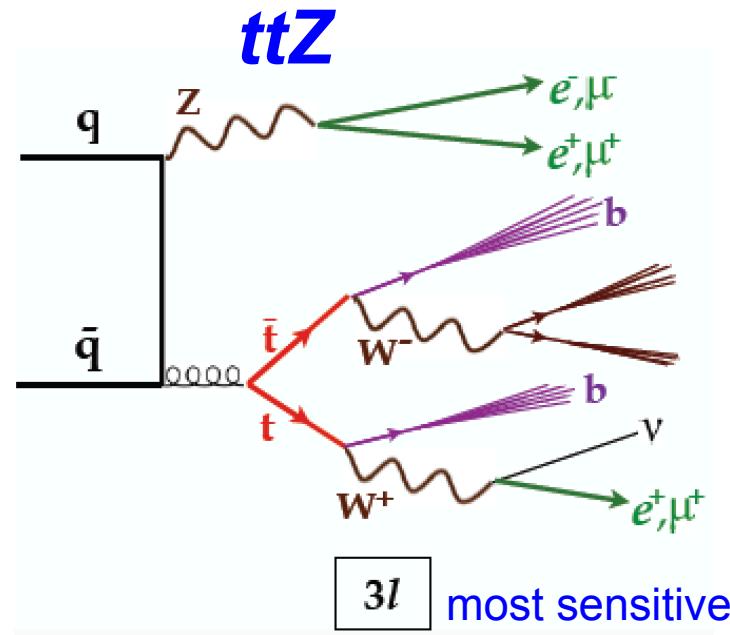
$$\sigma(\text{ttW}) = 1.50 \pm 0.72 \text{ (stat)} \pm 0.33 \text{ (syst)} \text{ pb}$$

- 2016 dataset (more than 25 fb⁻¹) currently being analysed → unique opportunity!! Further studies: EFT interpretation, fakes estimation, adding more channels, improving S/B separation including MVA or reconstruction techniques, differential XS measurements, ...



BACK-UP

ttZ and *ttW* signatures





Process	MC sample (ME+PS)	Normalisation (higher order theoretical prediction)
tt+ll on+off shell	MG5_aMC (LO mutileg)+Pythia8 (Np0+Np1)	NLO
ttZ(qq,nn)	MG5_aMC (LO mutileg)+Pythia8 (Np0+Np1+Np2)	NLO
ttW	MG5_aMC (LO mutileg)+Pythia8 (Np0+Np1+Np2)	NLO
tZ (s+t ch.)	MG5_aMC (LO)+Pythia6	NLO
tWZ	MG5_aMC (NLO)+Pythia8	NLO
ttWW	MG5_aMC (LO) +Pythia8	NLO
ttH	MG5_aMC (NLO)+Pythia8	NLO
Other Higgs prod.	Powheg (NLO)+Pythia8	NNLO(+NNLL) QCD and NLO EW
tt	Powheg (NLO)+Pythia6	NNLO+NNLL
Single top	Powheg (NLO)+Pythia6	aNNLO
Z+jets	Sherpa ME+PS@NLO	NLO
Dibosons	for ZZ & WW: Np0,1@NLO + Np2,3@LO For WZ: Np0@NLO + Np1,2,3@LO	
Tribosons	Sherpa LO (Np0+Np1+Np2)	LO
VBS	Sherpa LO Np0+Np1)	



Signal (ttZ and ttW) modelling

MG5_aMC@NLO+Pythia8 (A14 tune) multileg samples ($\text{ttV} \leq 1$ extra partons, $\text{ttW} \leq 2$ p) using $\mu = H_T$ and PDF set NNPDF2.3LO.
→ systematic uncertainties: alternative MC generator (Sherpa), scale choice and tune variations

Irreducible backgrounds

- tZ: MG5_aMC@NLO+Py6, CTEQ6L1, Perugia2012, 4 FS
- tWZ: MG5_aMC@NLO+Py8, NNPDF3.0NLO, A14, 5FS, diagram removal (ttZ)
- ttH: MG5_aMC@NLO+Py8, NNPDF3.0NLO, A14, 5FS
- VH: Py8, AZNLO tune; other Higgs: Powheg-Box v2 + Py8
- triboson $VVV \rightarrow 3l$ (LO) Sherpa 2.1, CT10, ≤ 2 extra partons; VBS ($l^{\pm} l^{\pm} vvjj$) Sherpa 2.1
- 3 or 4 top quarks: MG5_aMC@NLO+Py8, NNPDF2.3LO, A14

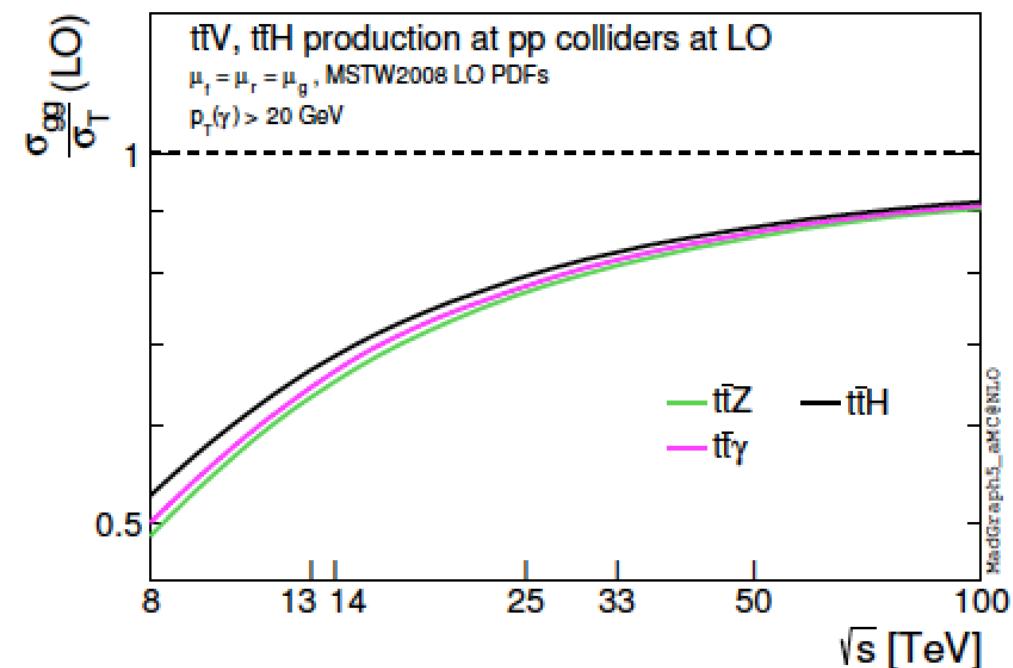
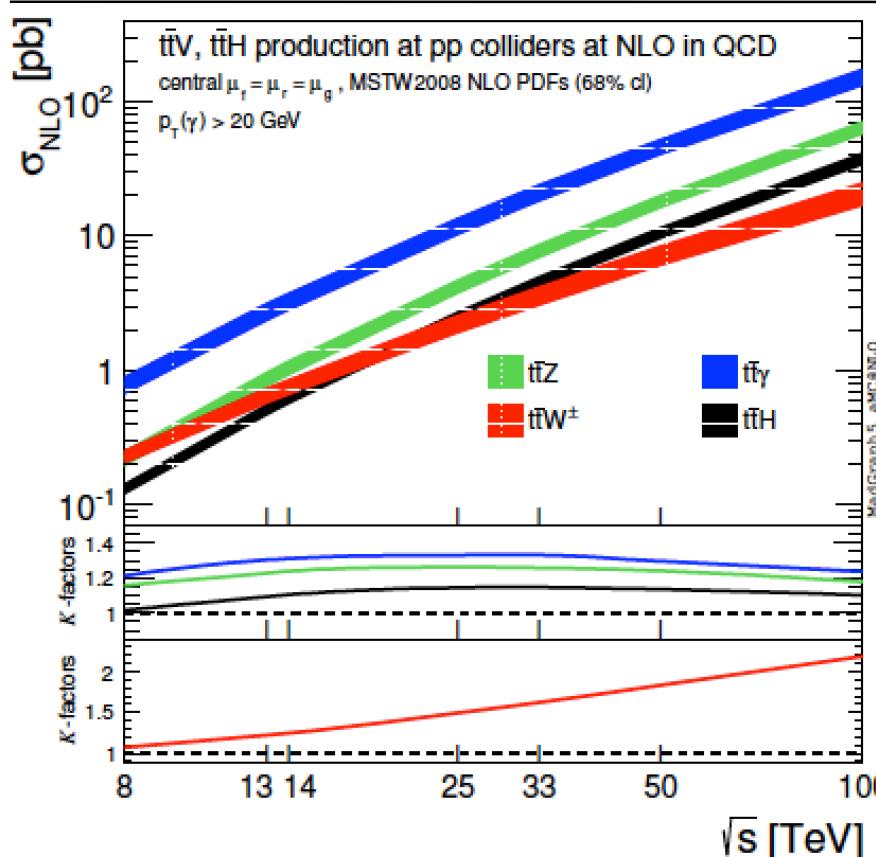
Data-driven backgrounds: modelling

- Dibosons: Sherpa 2.1: $4l$, $2l+2v$ with ≤ 1 extra parton and $3l+1v$ with no extra parton
→ WZ and ZZ normalisations are obtained from the fit to data including the CRs
- Processes with 2 opposite-sign leptons (or less, i.e. non-prompt: leptons):
tt, Wt: Powheg-Box v2+Py6
Z/W+jets: Sherpa 2.1
→ fake leptons determined with data driven methods

Process	XS [fb]	scale	pdf	alpha_S
ttZ	839.3	+ 9.6% -11.3%	$\pm 2.8\%$	$\pm 2.8\%$
ttW+	397.6	+12.7% -11.4%	$\pm 2.0\%$	$\pm 2.6\%$
ttW-	203.2	+13.3% -11.7%	$\pm 2.1\%$	$\pm 2.9\%$
ttW- + ttW+	600.8	+12.9% -11.5%	$\pm 2.0\%$	$\pm 2.7\%$

XS(ttZ) = 0.839 (+-12%) pb
XS(ttW) = 0.601 (+-13%) pb

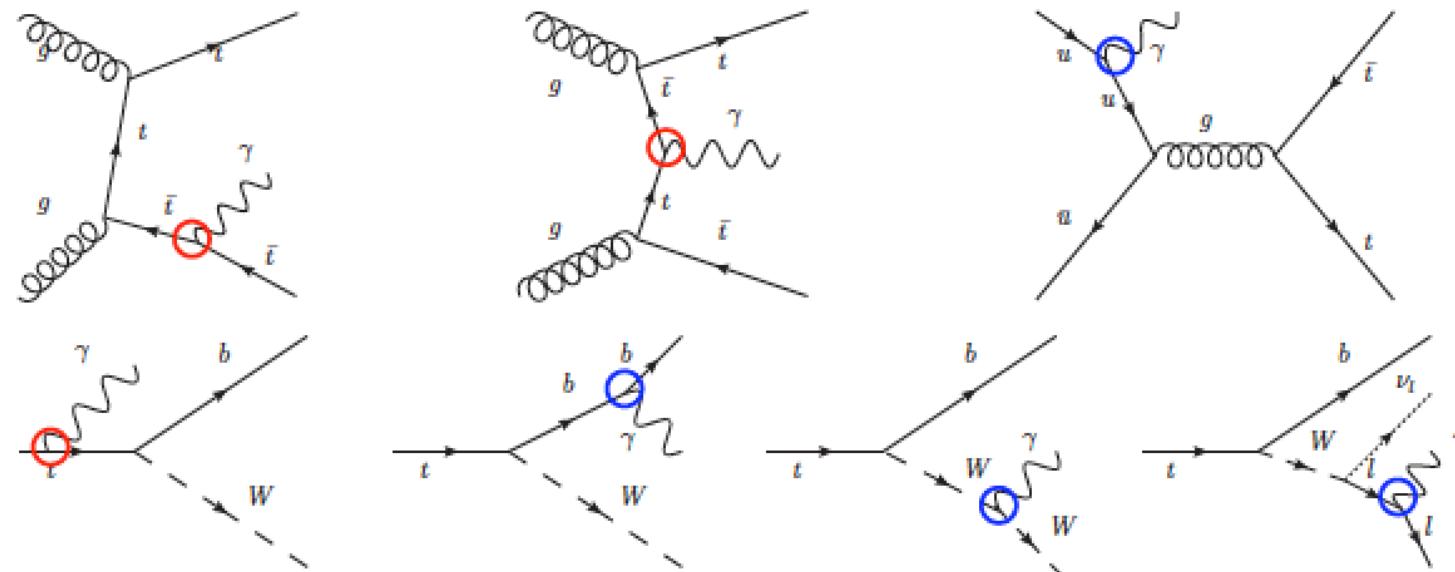
using fixed scale ($m_t + m_V/2$)



“Observation of top-quark pair production in association with a photon and measurement of the tt+ γ production cross section in pp collisions at 7 TeV using the ATLAS detector”

- Process not established before (1st evidence reported by CDF)
- Direct probing of t- γ coupling, BSM sensitivity (composite/excited top)
- Analysis performed in single lepton channel (more statistics)
- Events with 1 photon selected: γ radiation not from $t\bar{t}$ vertex (e.g. W γ , l γ or q γ vertex) suppressed by rejecting events with γ too close to leptons or jets

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- Events with fake photon(s) should be removed/subtracted:
 - hadron fake ($\text{jet} \rightarrow \gamma$): by exploiting the discrimination power of γ isolation
 - egamma fake ($e \rightarrow \gamma$): by estimating $e \rightarrow \gamma$ fake rate with Tag & Probe method
- Prompt γ backgrounds (minor: W, Z, single top, diboson) estimated from MC or data-driven

- Signal sample generated with MadGraph and WHIZARD
- Prompt and non-prompt gamma contributions estimated from data-driven template fit using the track isolation as discriminating variable.

Contribution	Electron chan.	Muon chan.	Total
Signal	52 ± 14	100 ± 28	152 ± 31
Hadrons	38 ± 26	55 ± 38	93 ± 46
Prompt photons	41 ± 5	65 ± 9	106 ± 10
Total background	79 ± 26	120 ± 39	199 ± 47
Total	131 ± 30	220 ± 48	351 ± 59
Data candidates	140	222	362

- Cross section per lepton flavor measured to be
 $\sigma_{\text{tt}\gamma} \times \text{BR} = 63^{+8(\text{stat.})^{+17}}_{-13(\text{syst.})} + 1(\text{lumi.}) \text{ fb}$
in a fiducial region

$p_T(\gamma/l/j) > 20/20/25 \text{ GeV}$

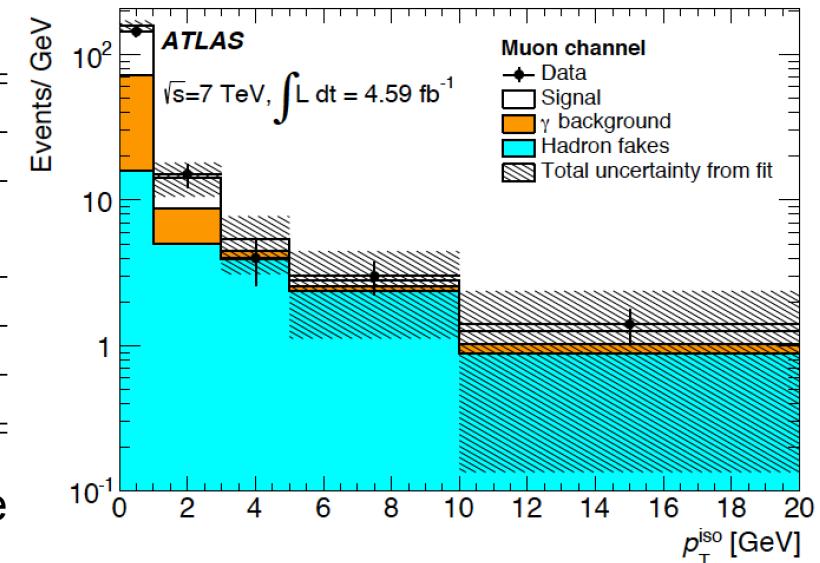
$\eta(\gamma/l/j) > 2.37/2.5/2.5$

$\Delta R(\gamma, j) > 0.5 \text{ and } \Delta R(\gamma, l) > 0.7$

Consistent with NLO calculation: $48 \pm 10 \text{ fb.}$

Signal significance of 5.3

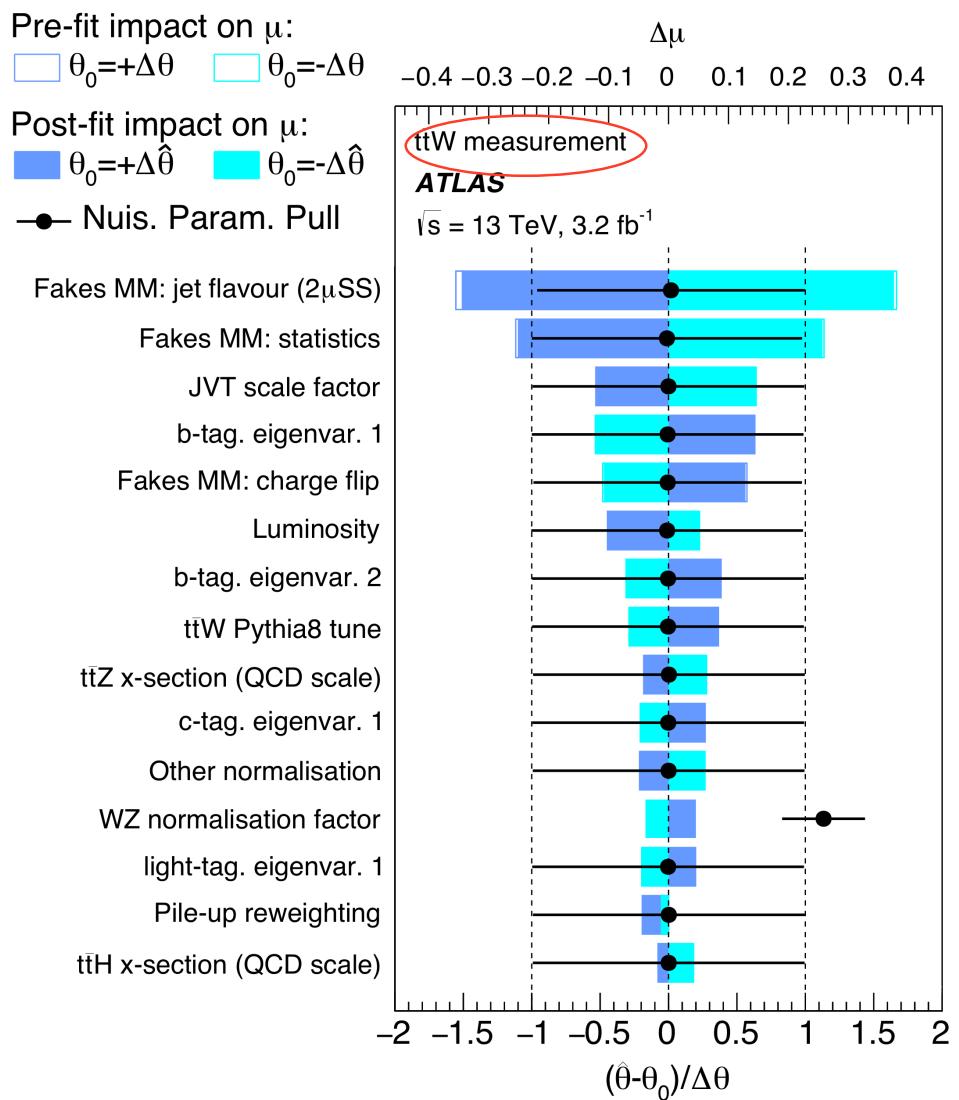
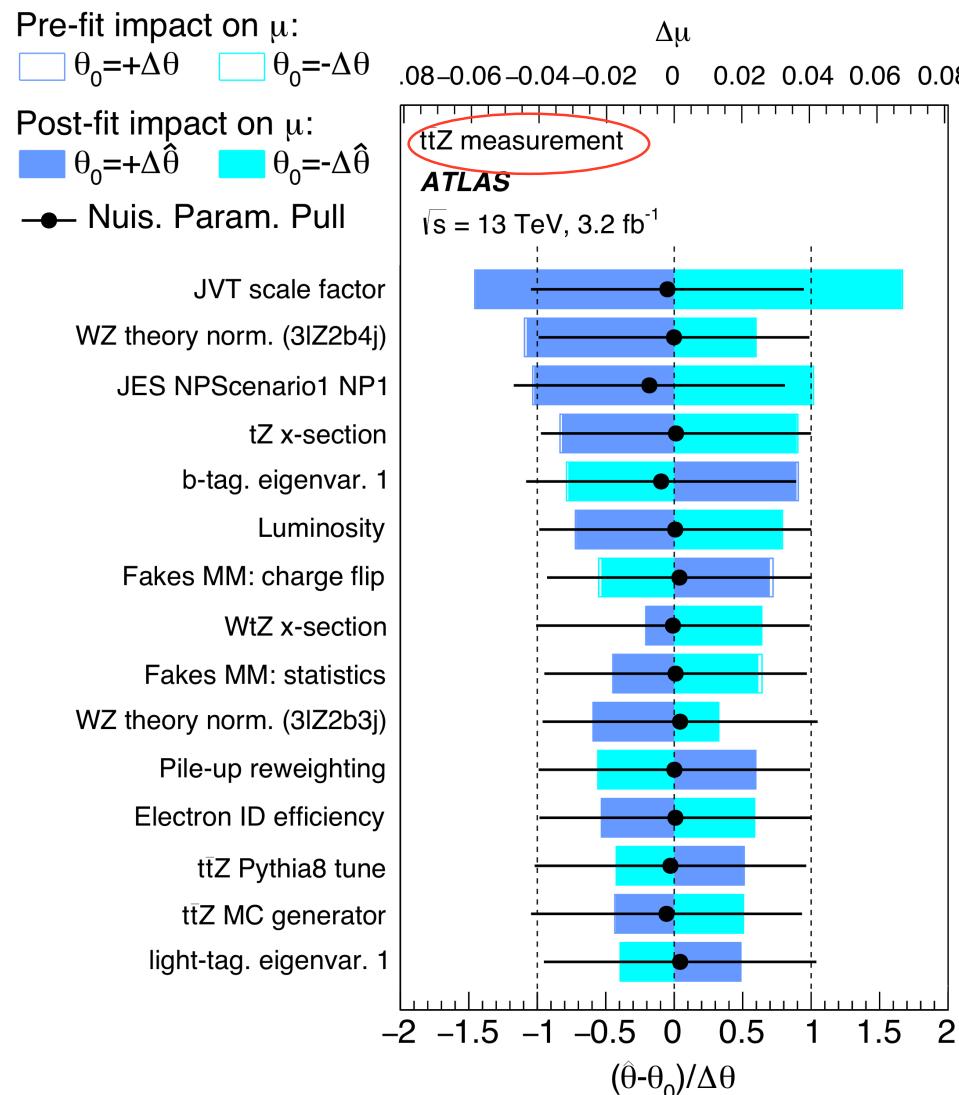
Systematics dominated by jet modelling

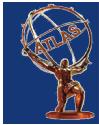


Uncertainty source	Uncertainty [%]
Background template shapes	3.7
Signal template shapes	6.6
Signal modeling	8.4
Photon modeling	8.8
Lepton modeling	2.5
Jet modeling	16.6
b -tagging	8.2
E_T^{miss} modeling	0.9
Luminosity	1.8
Background contributions	7.7



Region	$t + X$	Bosons	Fake leptons	Total bkg.	$t\bar{t}W$	$t\bar{t}Z$	Data
3 ℓ -WZ-CR	0.52 ± 0.13	26.9 ± 2.2	2.2 ± 1.8	29.5 ± 2.8	0.015 ± 0.004	0.80 ± 0.13	33
4 ℓ -ZZ-CR	< 0.001	39.5 ± 2.6	1.8 ± 0.6	41.2 ± 2.7	< 0.001	0.026 ± 0.007	39
2 μ -SS	0.94 ± 0.08	0.12 ± 0.05	1.5 ± 1.3	2.5 ± 1.3	2.32 ± 0.33	0.70 ± 0.10	9
3 ℓ -Z-2b4j	1.08 ± 0.25	0.5 ± 0.4	< 0.001	1.6 ± 0.5	0.065 ± 0.013	5.5 ± 0.7	8
3 ℓ -Z-1b4j	1.14 ± 0.24	3.3 ± 2.2	2.2 ± 1.7	6.7 ± 2.8	0.036 ± 0.011	4.3 ± 0.6	7
3 ℓ -Z-2b3j	0.58 ± 0.19	0.22 ± 0.18	< 0.001	0.80 ± 0.26	0.083 ± 0.014	1.93 ± 0.28	4
3 ℓ -noZ-2b	0.95 ± 0.11	0.14 ± 0.12	3.6 ± 2.2	4.7 ± 2.2	1.59 ± 0.28	1.45 ± 0.20	10
4 ℓ -SF-1b	0.212 ± 0.032	0.09 ± 0.07	0.113 ± 0.022	0.42 ± 0.08	< 0.001	0.66 ± 0.09	1
4 ℓ -SF-2b	0.121 ± 0.021	0.07 ± 0.06	0.062 ± 0.012	0.25 ± 0.07	< 0.001	0.63 ± 0.09	1
4 ℓ -DF-2b	0.25 ± 0.04	0.0131 ± 0.0032	0.114 ± 0.019	0.37 ± 0.04	< 0.001	0.75 ± 0.10	2
4 ℓ -DF-1b	0.16 ± 0.05	< 0.001	0.063 ± 0.013	0.23 ± 0.05	< 0.001	0.64 ± 0.09	1





2 μ SS: matrix method

- separately for b-tagged and b-vetoed events
- ϵ_{real} from OS dilepton events
- ϵ_{fake} from SS dilepton events not in SR (high MET)

3l: matrix method

- same efficiencies as in 2 μ -SS region

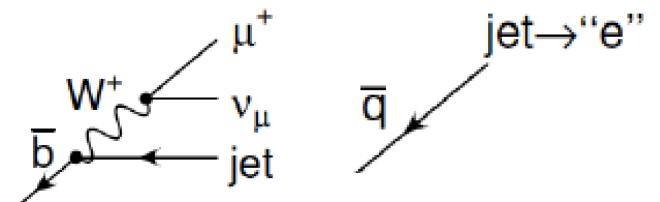
4l: fake factor method

- 4 scale factors: lepton (e, μ) x fake source (heavy, light)
- Define 3l regions enriched with fake leptons
 - tt selection \rightarrow heavy flavour $FF_{e,tt}$, $FF_{\mu,tt}$
 - Z+jets selection \rightarrow light flavour $FF_{e,Z}$, $FF_{\mu,Z}$
- apply to all simulation samples with less than four true leptons

Non-prompt leptons: semileptonic b-decays, jet fakes

2 μ SS and 3l:

- main sources: ttbar in 2ISS, ttbar and Z+jets in 3l
- estimated from data-driven technique: **matrix method**
 - define control regions with looser lepton requirements to derive real and fake lepton efficiencies as function of the lepton p_T , separately for electrons and muons
 - select dileptonic (ee , $\mu\mu$ and $e\mu$) events with OS or SS
 - classify events into N_{TT} , N_{TL} , N_{LT} , N_{LL}
 - build likelihood functions from poissonian constraints on observed N_{ij}



$$r = \frac{N_R^T}{N_R^L}, \quad f = \frac{N_F^T}{N_F^L}$$

$$L = \prod_{ij} \prod_m Po(N_{ij}^m | M_{ij}^{mn}(r_i, f_i, r_j, f_j) n_{ij}^n)$$

$$N_{ij}^m = M_{ij}^{mn} n_{ij}^n,$$

$$N_{ij}^m = \begin{pmatrix} N_{TT} \\ N_{TL} \\ N_{LT} \\ N_{LL} \end{pmatrix}_{ij},$$

$$n_{ij}^n = \begin{pmatrix} N_{RR}^{ll} \\ N_{RF}^{ll} \\ N_{FR}^{ll} \\ N_{FF}^{ll} \end{pmatrix}_{ij},$$

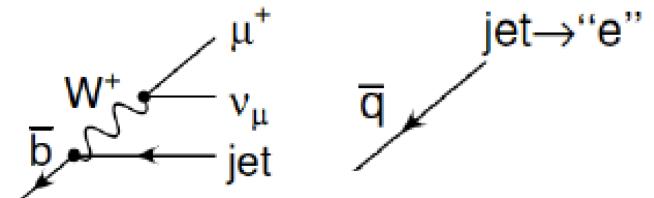
$$M_{ij}^{mn} = \begin{pmatrix} r_i r_j & r_i f_j & f_i r_j & f_i f_j \\ r_i(1-r_j) & r_i(1-f_j) & f_i(1-r_j) & f_i(1-f_j) \\ (1-r_i)r_j & (1-r_i)f_j & (1-f_i)r_j & (1-f_i)f_j \\ (1-r_i)(1-r_j) & (1-r_i)(1-f_j) & (1-f_i)(1-r_j) & (1-f_i)(1-f_j) \end{pmatrix} \longrightarrow n_{ij}^n = (M^{nm})_{ij}^{-1} N_{ij}^m$$

- * m is the index for the four different loose not tight (L) and tight (T) event configurations and n the four unknown fake lepton (F) and real lepton (R) event configurations.
- * The indices i and j are the binning of the leading and subleading leptons, assuming a 1D parametrisation, in p_T

Non-prompt leptons: semileptonic b-decays, jet fakes

2μSS and 3l:

- main sources: ttbar in 2ISS, ttbar and Z+jets in 3l
- estimated from data-driven technique: **matrix method**
 - define control regions with looser lepton requirements to derive real and fake lepton efficiencies as function of the lepton p_T , separately for electrons and muons
 - select dileptonic (ee , $\mu\mu$ and $e\mu$) events with OS or SS
 - classify events into N_{TT} , N_{TL} , N_{LT} , N_{LL}
 - build likelihood functions from poissonian constraints on observed N_{ij}



$$r = \frac{N_R^T}{N_R^I}, \quad f = \frac{N_F^T}{N_F^I}$$

Variable	OS_r	SS_f
Leptons		≈ 2
Leading lepton p_T	> 25 GeV	
Second lepton p_T	> 15 GeV	
Dilepton mass	> 15 GeV	
n_{jets}		≥ 1
Charge	opposite-sign	same-sign
Lepton flavor	$ee, \mu\mu$	$ee, \mu\mu, e\mu$
$n_{b-\text{jets}}$	≈ 0	≈ 0
E_T^{miss}	≥ 1	≥ 1
E_T^{miss}	-	> 40 GeV
Z-veto(ee)	no	yes
$n_{b-\text{jets}} < 2$ ($\mu\mu$)	no	yes

The minimisation is performed twice:
once to solve for r (using OS Z events), and
a second time with r held fixed to solve for f
(using SS events).

Constrains:

$$N_{FF} = 0$$

$$r_i = r_j \text{ for same same lepton flavour}$$

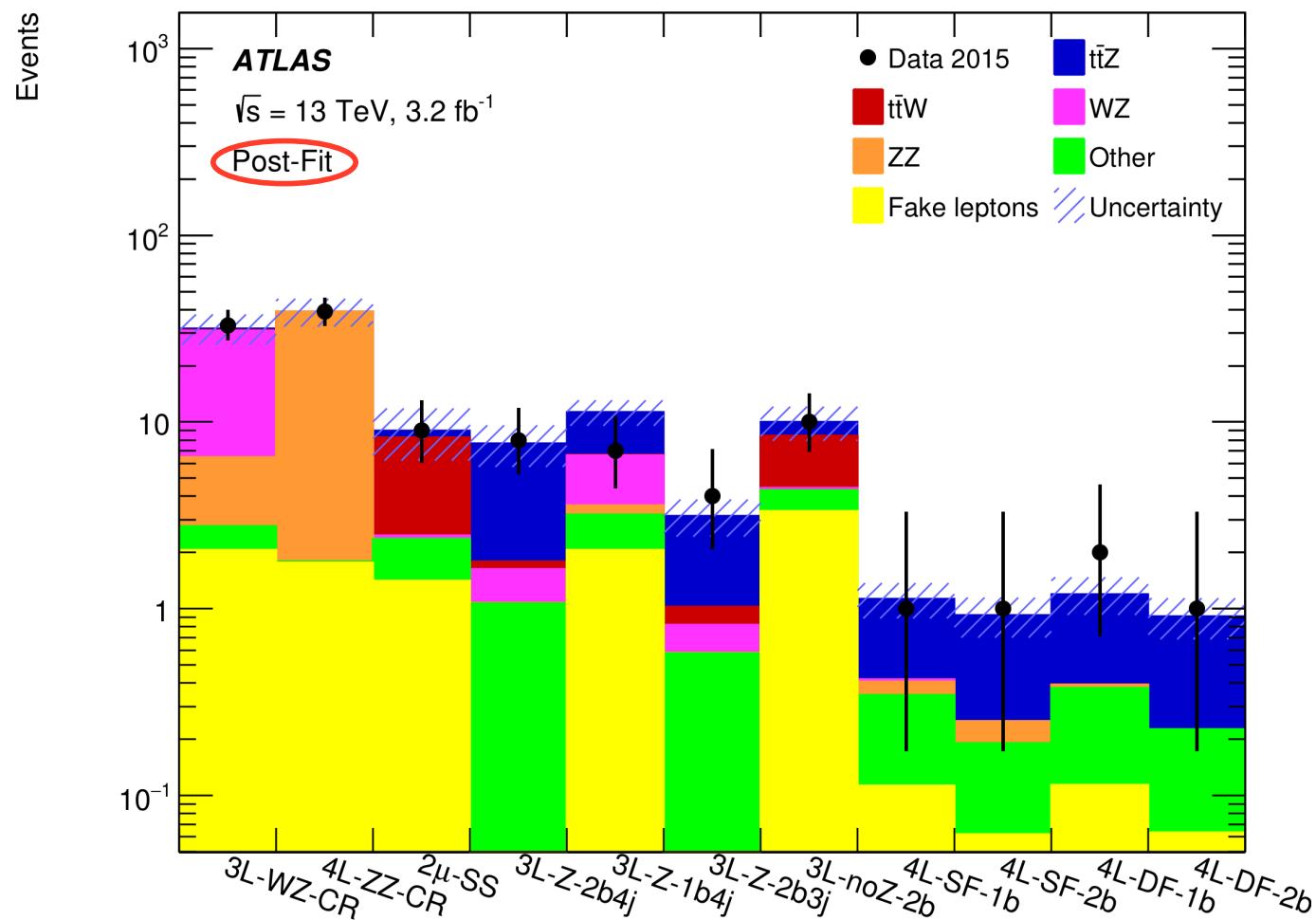
$$N_{RR} = 0 \text{ in SS regions}$$



Methodology

- Goal: Correct fake rates in the signal regions by scaling MC events with fake leptons
- Define regions enriched with fake leptons
 - Heavy flavour fakes (e or μ): $3\ell t\bar{t}$ control region
 - Light flavour fakes (e or μ): $3\ell Z$ control region
→ 4 control regions
- Determination of fake electron factors
 - α_{light}^e and α_{heavy}^e are determined simultaneously from:

$$Data_e^{CR} - MC, Other_e^{CR} = \alpha_{heavy}^e t\bar{t}_e^{CR} + \alpha_{light}^e Z_e^{CR}$$
 - Solve the 2 equations (CR=Z and CR=t \bar{t}) for the fake electron factors α_{light}^e and α_{heavy}^e
- Determination of fake muon factors is analogous
- Apply fake factors to the MC:
 - 1 Check whether fake e or μ is present using truth information
 - 2 Apply α_{heavy}^e or α_{heavy}^μ for all MCs with heavy flavour quarks
 - 3 Apply α_{light}^e or α_{light}^μ for all other MCs

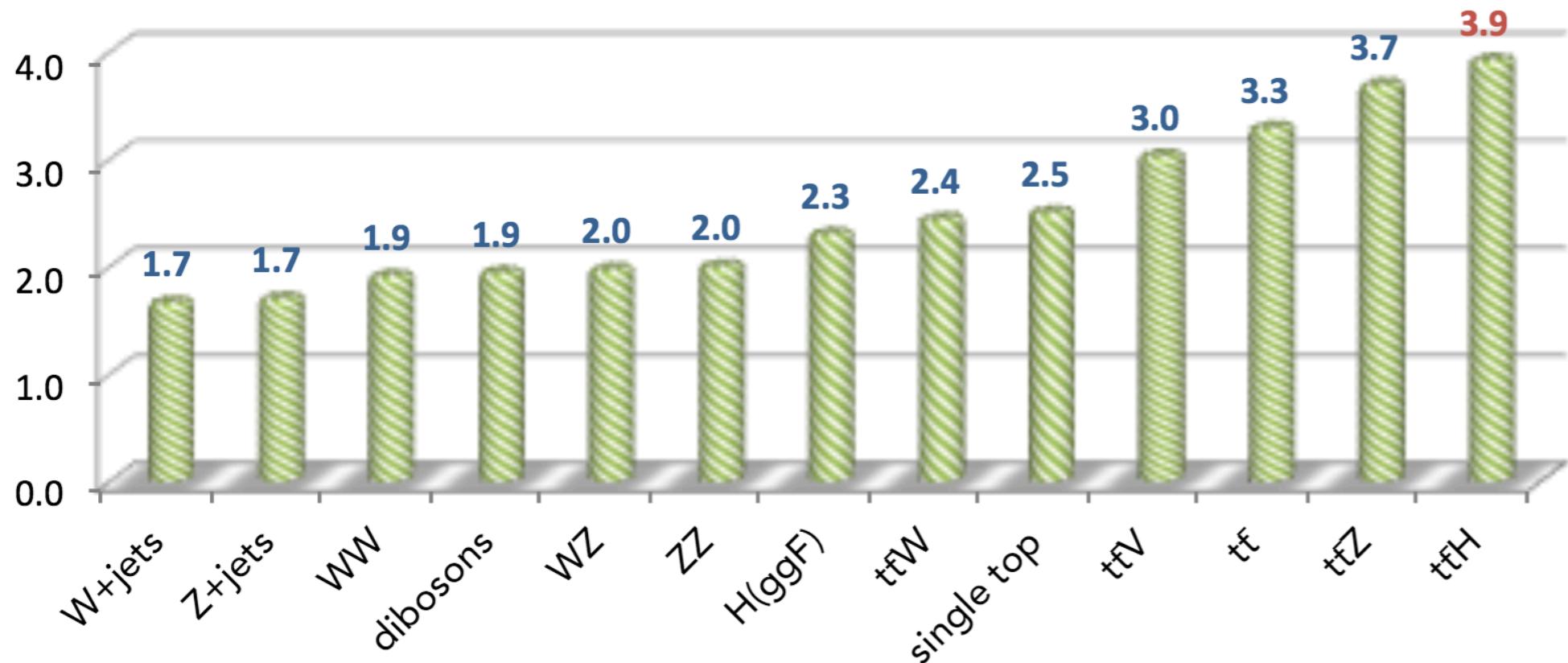


ttZ cross-section measurement (8SRs+2CRs)
 WZ_norm 1.10 ± 0.30
 ZZ_norm 0.94 ± 0.17
 mu_XS_ttZ 1.15 ± 0.37
 $\rightarrow XS(t\bar{t}Z) = 0.97 \pm 0.29 \text{ (stat)} \pm 0.10 \text{ (syst)} \text{ pb}$

ttW cross-section measurement (2SRs+2CRs)
 WZ_norm 1.13 ± 0.30
 ZZ_norm 0.94 ± 0.17
 mu_XS_ttW 2.45 ± 1.31
 $\rightarrow XS(t\bar{t}W) = 1.47 \pm 0.72 \text{ (stat)} \pm 0.33 \text{ (syst)} \text{ pb}$

Increase of expected cross section in Run 2 → more tt+X events in Run2 !!!!!

Cross section ratios 13 TeV / 8 TeV



Process	$\sigma(8\text{TeV})$	$\sigma(13\text{TeV})$	$\sigma(13\text{TeV})/\sigma(8\text{TeV})$
$t\bar{t}Z$	0.206 pb	0.760 pb	3.7
tZ (t+s ch.)	0.236 pb	t-ch: 0.7 pb t-ch: 0.4(LO)/0.5657(NLO) s-ch: 0.010(LO)/0.015(NLO) pb	
tWZ	~0.03 pb	0.156 pb	4.7
ttW	0.203-0.232pb	0.566 pb	2.8
ttH	0.129 pb	0.5085 pb	3.9
tH (t+s ch.)	0.0187+0.0012=0.02 pb or 0.0138 pb	0.063 pb (includes s-ch?) or 0.0743 pb	~3
tWH	0.005 pb	0.025 pb	~5
$tt\bar{b}$	~250 pb	~830 pb	3.3
single top	87+5.7+22.0=114.7 pb	218+11.2+70.4=299.6 pb	2.6
ZZ ($m_Z > 60\text{GeV}$)	8.8 pb	15.8 pb	1.8
WW	66.1	117.5	1.8
WZ	27.5	51.3	1.9
$Z(\rightarrow \ell^+\ell^-) + \text{jets}$	~1120 pb	~1906 pb	1.7
$W(\rightarrow \ell^\pm v) + \text{jets}$	~12000 pb	~20000 pb	1.7

How to measure top couplings?

The top quark couples to other SM fields through its **gauge and Yukawa interactions**
 $t \rightarrow Wb$ coupling measured already at the Tevatron

High statistics at the LHC: $t\bar{t}$ +bosons (g , Z and H) becomes available!!

First evidence on the coupling of the top quark to these particles from production rate

Important SM test: **new physics** modifies the structure of the couplings

