Top-quark pair production in association with a *W* or *Z* boson with the ATLAS experiment

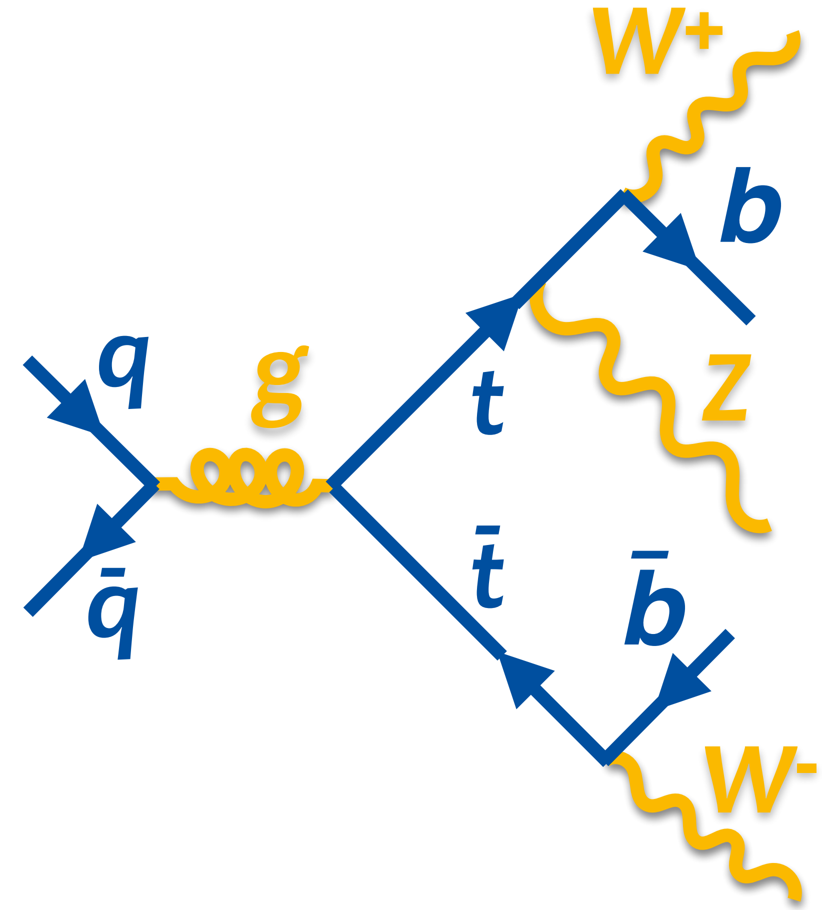
Sebastian Heer
Universität Bonn
on behalf of the ATLAS experiment

September 18th
Top 2018 conference
Bad Neuenahr

Introduction

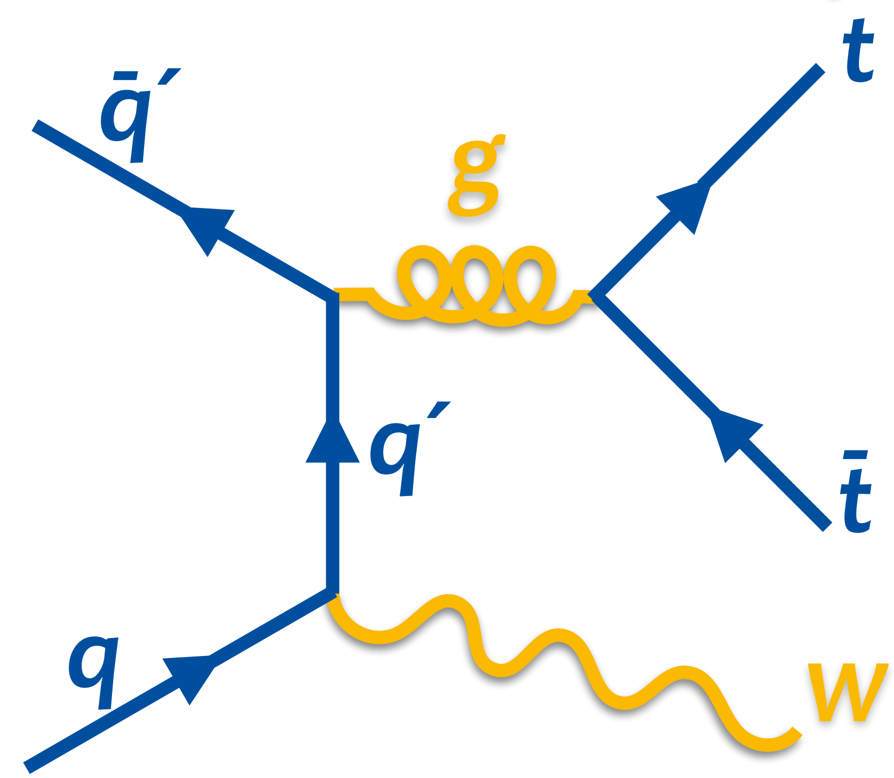
Motivation to study $t\bar{t}V$

- Test EW SM prediction
- $t\bar{t}Z$: sensitive to tZ coupling
- $t\bar{t}W$: $q\bar{q}$ initial state only, rare source of same-sign leptons
- Sensitive to EFT operators
  - $O^{(3)}_{\phi Q}$-$O^{(1)}_{\phi Q}$, $O_{\phi t}$, O_{tW} & O_{tB}



Previous $t\bar{t}V$ measurements at 13 TeV

- ATLAS Analysis with 3.2 fb^{-1}:
  [EPJC 77 (2017) 40]
  - First $t\bar{t}V$ measurement at 13 TeV
- CMS Analysis with 35.9 fb^{-1}:
  [JHEP 08 (2018) 011]



New Result

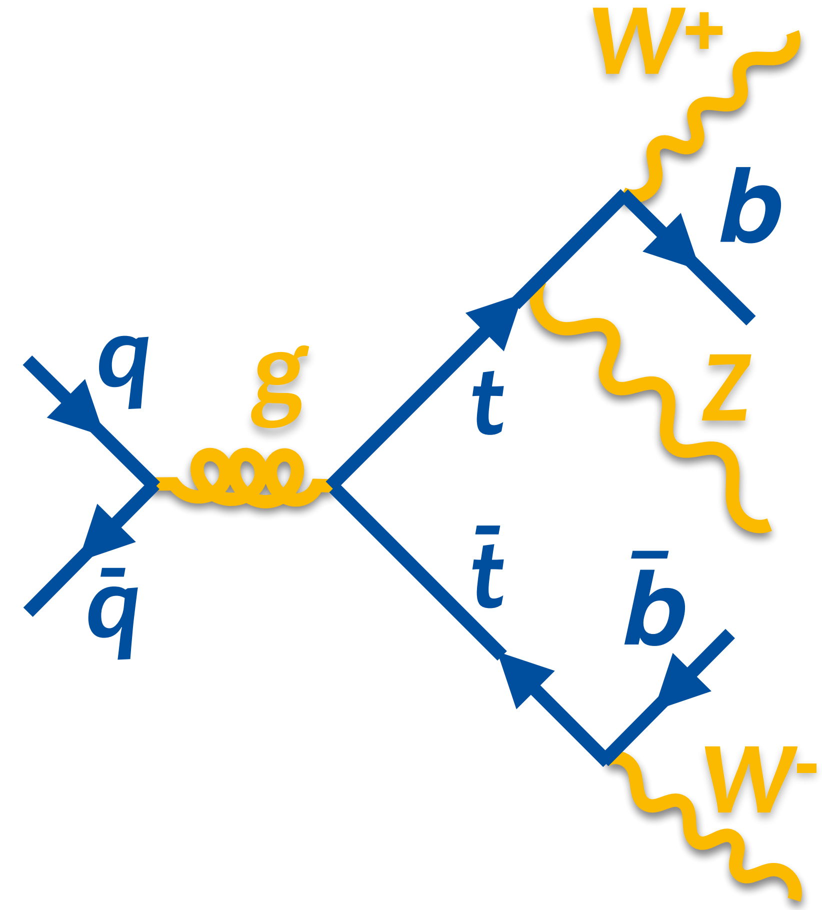
- ATLAS measurement with 36.1 fb^{-1}:
  ATLAS-CONF-2018-047

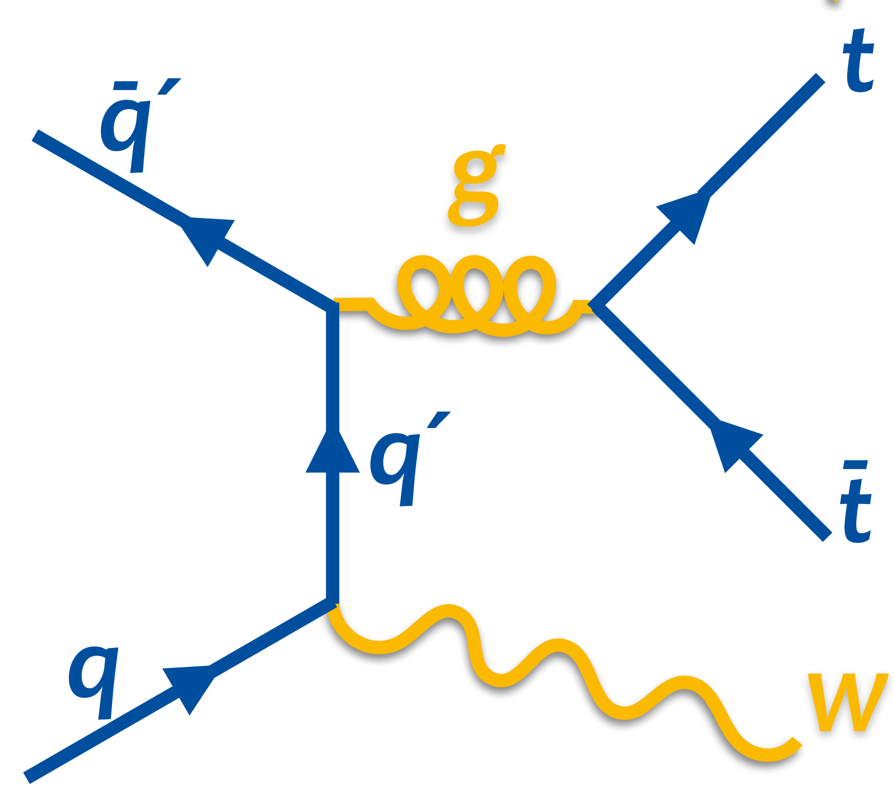
Analysis Strategy

- Multiple channels based on number of leptons
  - multiple signal regions per channel
- Perform a 2D profile likelihood fit, extracting both cross sections
- Add normalisations of irreducible backgrounds to the fit as free parameters

Process	$t\bar{t}$ decay	Boson decay	Channel
$t\bar{t}W$	$(\ell^{\pm}\nu b)(q\bar{q}b)$	$\ell^{\pm}\nu$	SS dilepton
	$(\ell^{\pm}\nu b)(\ell^{\mp}\nu b)$	$\ell^{\pm}\nu$	Trilepton
$t\bar{t}Z$	$(q\bar{q}b)(q\bar{q}b)$	$\ell^{+}\ell^{-}$	OS dilepton
	$(\ell^{\pm}\nu b)(q\bar{q}b)$	$\ell^{+}\ell^{-}$	Trilepton
	$(\ell^{\pm}\nu b)(\ell^{\mp}\nu b)$	$\ell^{+}\ell^{-}$	Tetralepton

- Focus of this talk: 4ℓ channel targeting $t\bar{t}Z$
- An overview was given by Clara Nellist this afternoon



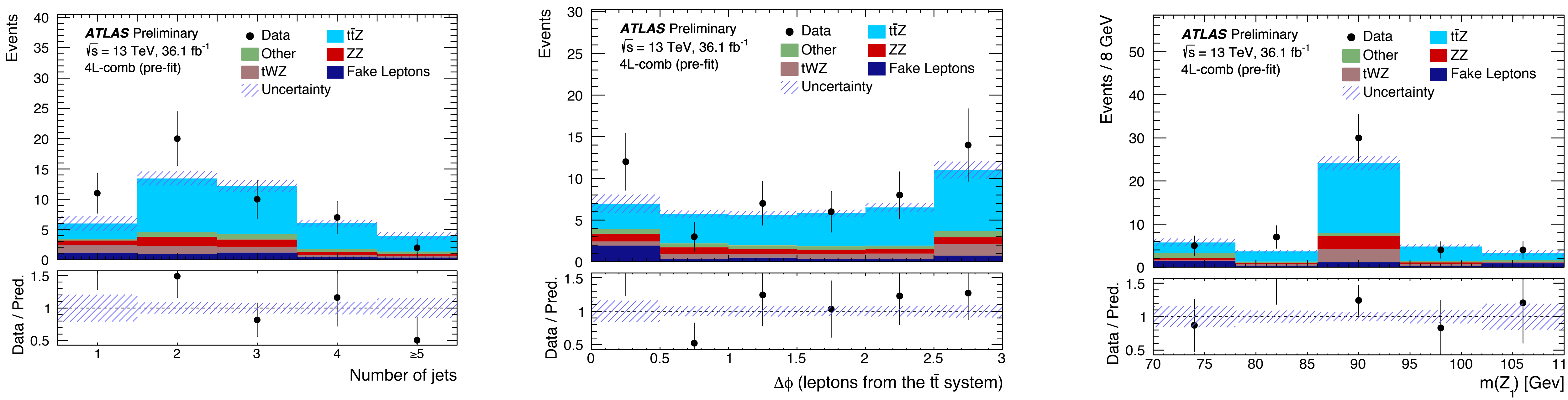


4ℓ channel ($t\bar{t}Z$)

- 4 signal regions according to *b*-jet multiplicity and lepton flavour
  - Z_1 = pair closest to *Z* mass, Z_2 = remaining two leptons

Region	Z_2 leptons	p_{T4}	p_{T34}	$\lvert m_{Z_2} - m_Z \rvert$	E_T^{miss}	$n_{b\text{-tags}}$
4ℓ-DF-1b	$e^{\pm}\mu^{\mp}$	-	> 35 GeV	-	-	1
4ℓ-DF-2b	$e^{\pm}\mu^{\mp}$	> 10 GeV	-	-	-	≥ 2
4ℓ-SF-1b	$e^{\pm}e^{\mp}$, $\mu^{\pm}\mu^{\mp}$	-	> 25 GeV	> 10 GeV < 10 GeV	> 40 GeV > 80 GeV	1
4ℓ-SF-2b	$e^{\pm}e^{\mp}$, $\mu^{\pm}\mu^{\mp}$	> 10 GeV	-	> 10 GeV < 10 GeV	- > 40 GeV	≥ 2

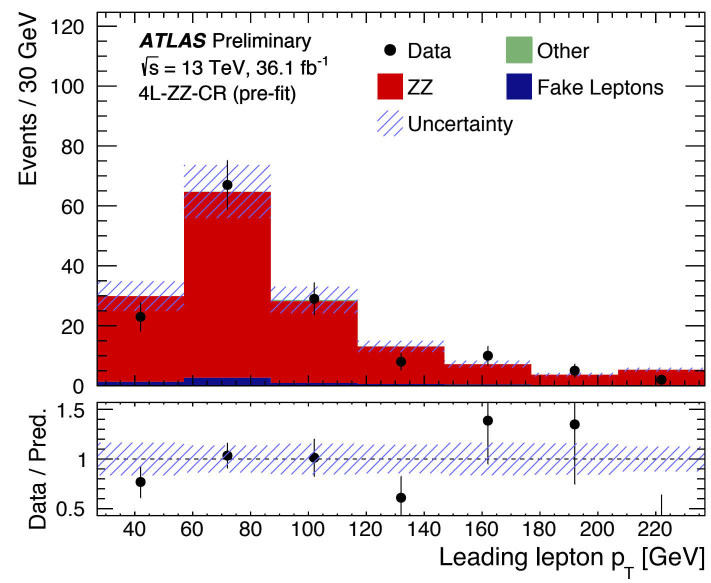
- important backgrounds: diboson, *tWZ* and fake leptons
  - *ZZ* normalisation is a free parameters of the fit
- Scale factors in $t\bar{t}$ and *Z*+Jets control regions are determined for fake electrons and muons

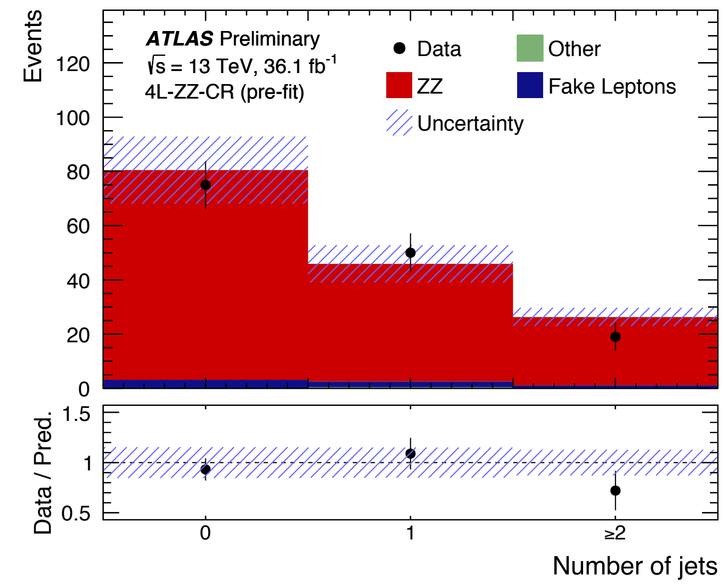


4ℓ channel ($t\bar{t}Z$)

4ℓ-ZZ-CR

- 20 GeV < E_T^{miss} < 40 GeV
- $|m_{Z1,2}$ - 91.2 GeV$|$ < 10 GeV
- 2 SF lepton pairs





- Orthogonal to signal regions by the E_T^{miss} requirement
- Good modelling
- Extrapolation uncertainty on *ZZ* for transition of control region to signal region of 20-40%
  - Assessed by varying renormalization, factorization and resummation scales used in MC generation

Fit result (4ℓ channel only)

Significance
5.7σ (5.1)σ

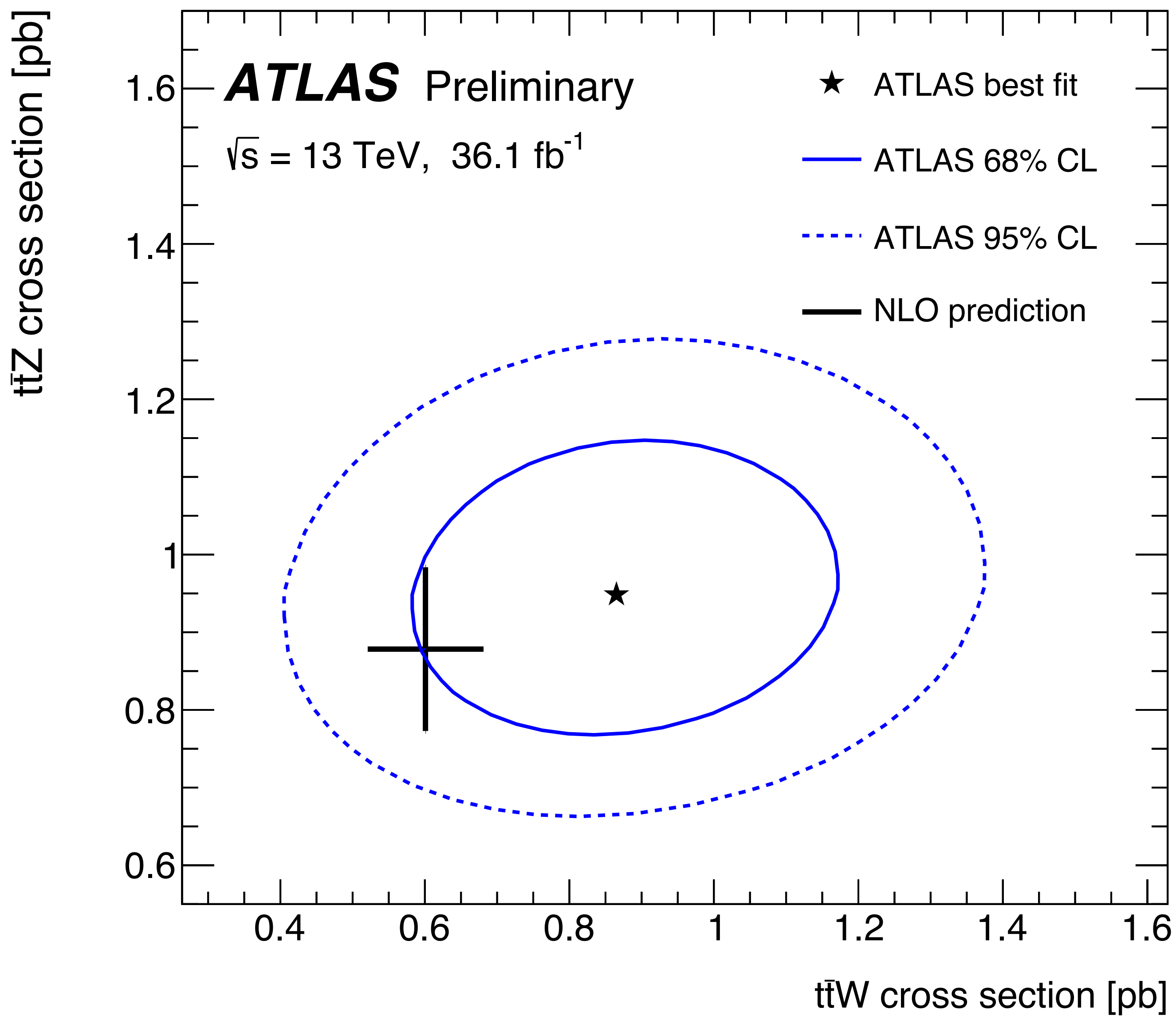
$$\mu_{ZZ} = 0.94 \pm 0.09\,(\text{stat.}) \pm 0.16\,(\text{syst.})$$

$$\mu_{t\bar{t}Z} = 1.21^{+0.28}_{-0.25}\,(\text{stat.})\,^{+0.11}_{-0.12}\,(\text{syst.})$$

Results for all channels

Fit configuration	$\mu_{t\bar{t}Z}$	$\mu_{t\bar{t}W}$
Combined	1.08 ± 0.14	1.44 ± 0.32
2ℓ-OS	0.73 ± 0.28	-
3ℓ $t\bar{t}Z$	1.08 ± 0.18	-
2ℓ-SS and 3ℓ $t\bar{t}W$	-	1.41 ± 0.33
4ℓ	1.21 ± 0.29	-

Uncertainty	$\sigma_{t\bar{t}Z}$	$\sigma_{t\bar{t}W}$
Luminosity	2.9%	4.5%
CR and simulated sample statistics	1.8%	7.6%
JES/JER	1.9%	4.1%
Flavor tagging	4.2%	3.7%
Other object-related	3.7%	2.5%
Data-driven background normalization	2.4%	3.9%
Modeling of backgrounds from simulation	5.3%	2.6%
Background cross sections	2.3%	4.9%
Fake leptons and charge misID	1.8%	5.7%
$t\bar{t}Z$ modeling	4.9%	0.7%
$t\bar{t}W$ modeling	0.3%	8.5%
Total systematic	10%	16%
Statistical	8.4%	15%
Total	13%	22%



$t\bar{t}Z$

σ_{exp} = 0.95 ± 0.13 pb
σ_{theo} = 0.88 ± 0.08 pb
>>5σ

$t\bar{t}W$

σ_{exp} = 0.87 ± 0.19 pb
σ_{theo} = 0.60 ± 0.10 pb
4.3σ (3.4σ)

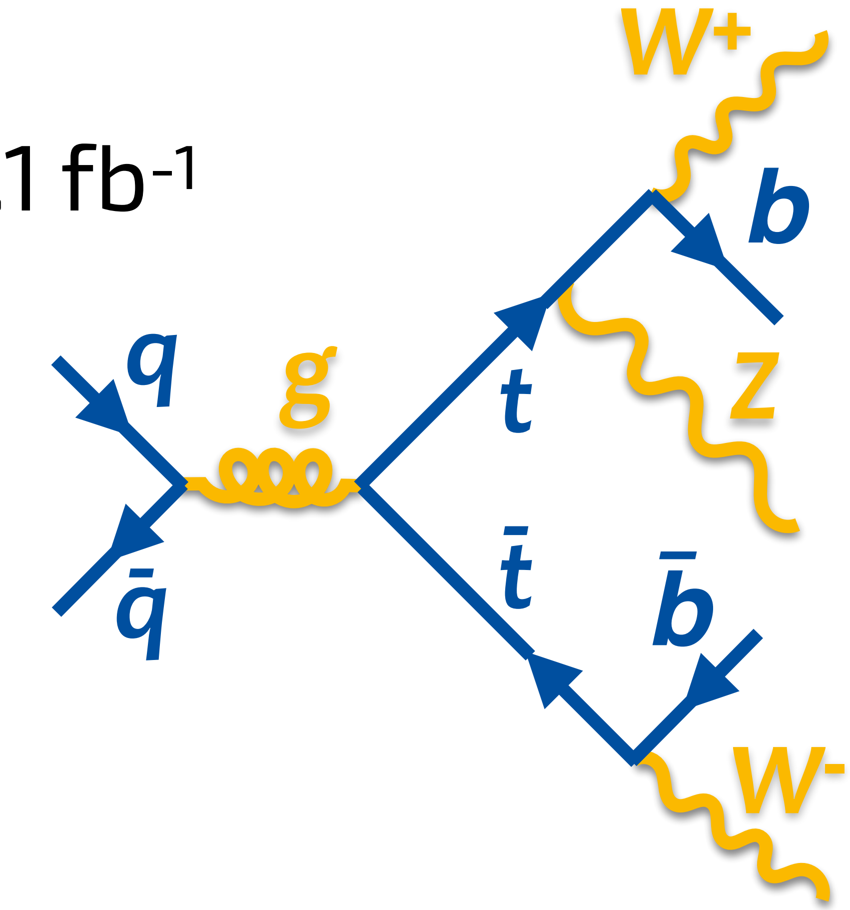
Conclusions

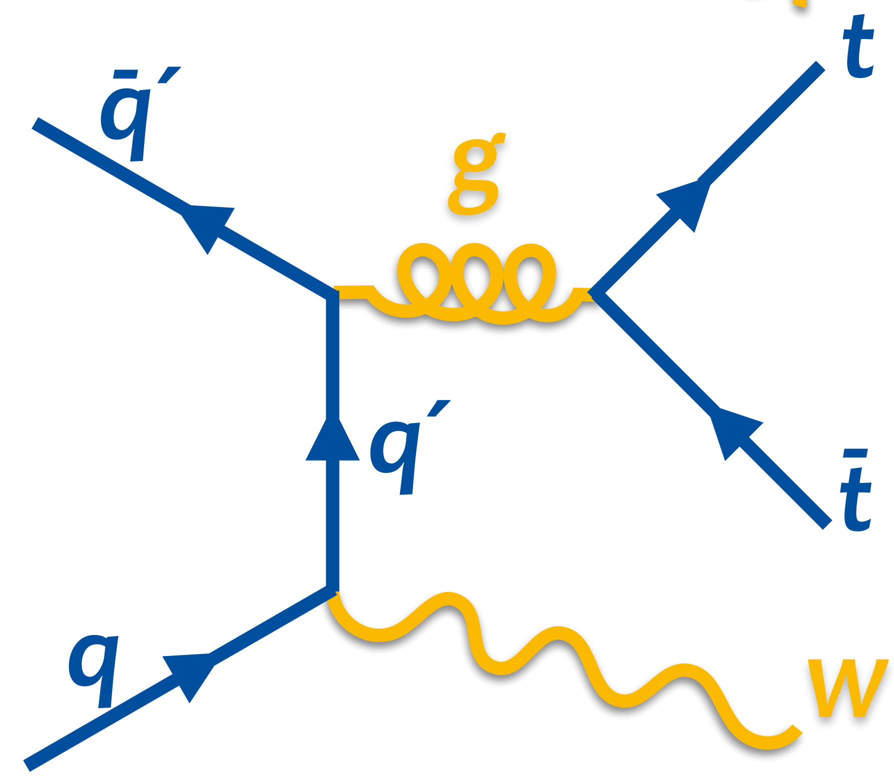
Conclusions

- Recent ATLAS Measurement with 36.1 fb^{-1}
- Cross sections extracted in 2D fit
  - Agreement with SM within the uncertainties

Process	$t\bar{t}$ decay	Boson decay	Channel
$t\bar{t}W$	$(\ell^{\pm}\nu b)(q\bar{q}b)$	$\ell^{\pm}\nu$	SS dilepton
	$(\ell^{\pm}\nu b)(\ell^{\mp}\nu b)$	$\ell^{\pm}\nu$	Trilepton
$t\bar{t}Z$	$(q\bar{q}b)(q\bar{q}b)$	$\ell^{+}\ell^{-}$	OS dilepton
	$(\ell^{\pm}\nu b)(q\bar{q}b)$	$\ell^{+}\ell^{-}$	Trilepton
	$(\ell^{\pm}\nu b)(\ell^{\mp}\nu b)$	$\ell^{+}\ell^{-}$	Tetralepton

ATLAS-CONF-2018-047





More on this analysis at Top2018

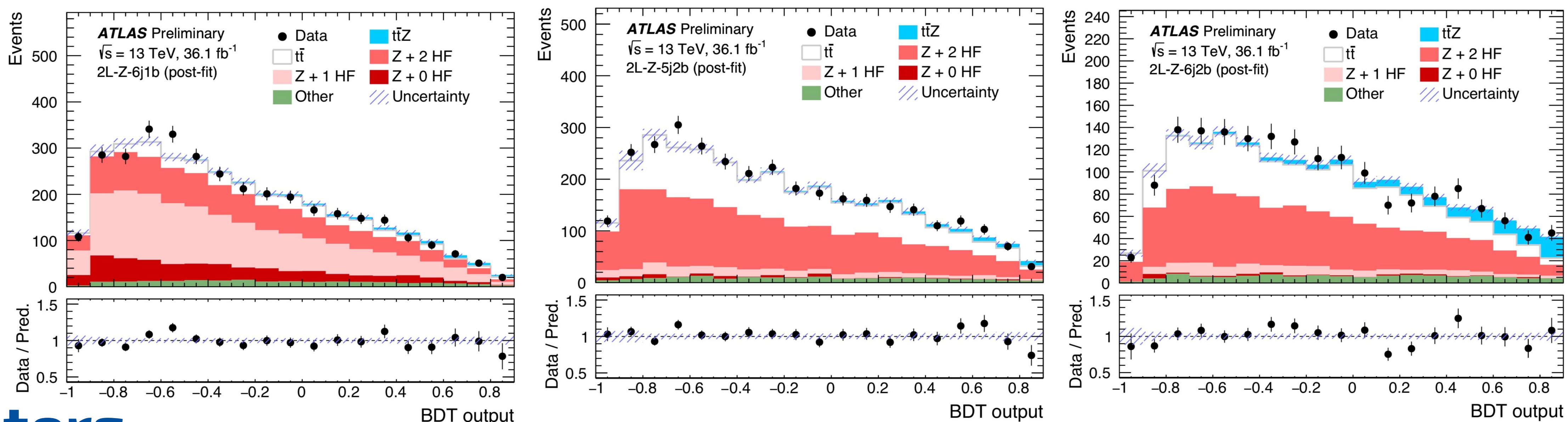
- Poster
- Talk by Clara Nellist this afternoon

BACKUP

BACKUP - $t\bar{t}Z$ analysis overview

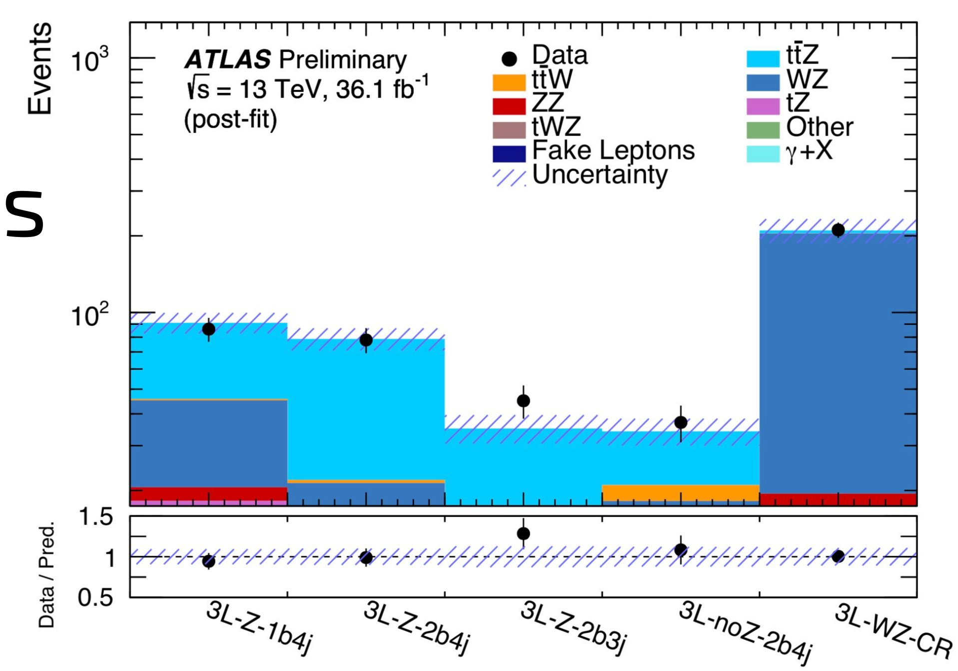
3 analysis channels

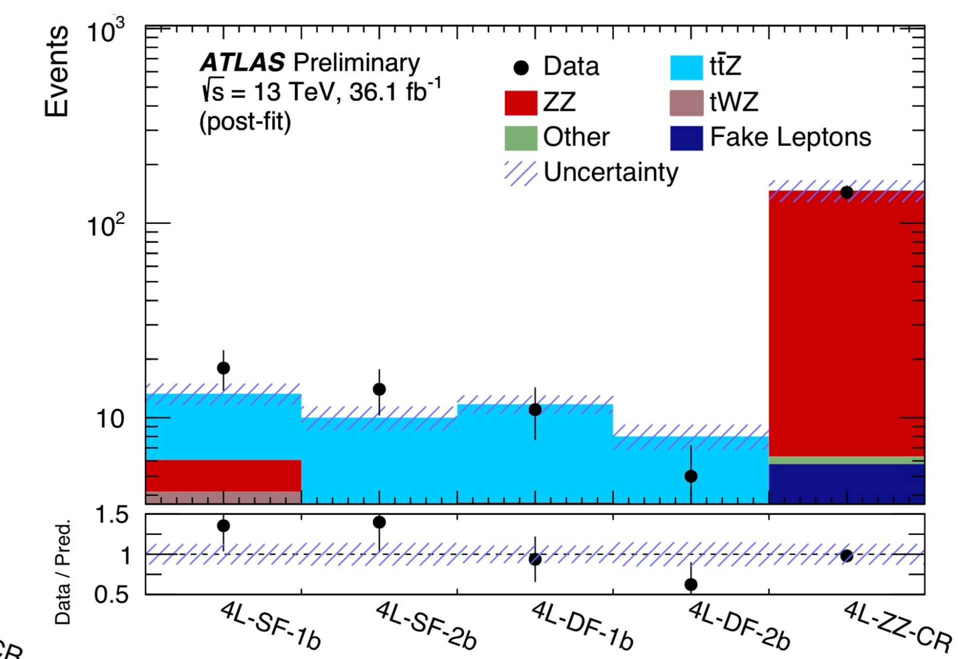
- 2ℓOS: three BDTs, according to jet multiplicity
- 3ℓ: four signal regions & 1 *WZ* CR
- 4ℓ: four signal regions & 1 ZZ CR



Fit parameters

- $\mu(t\bar{t}Z)$
- normalistations
  - *Z*+1 jet (HF)
  - *Z*+2 jets (HF)
  - *WZ*
  - *ZZ*





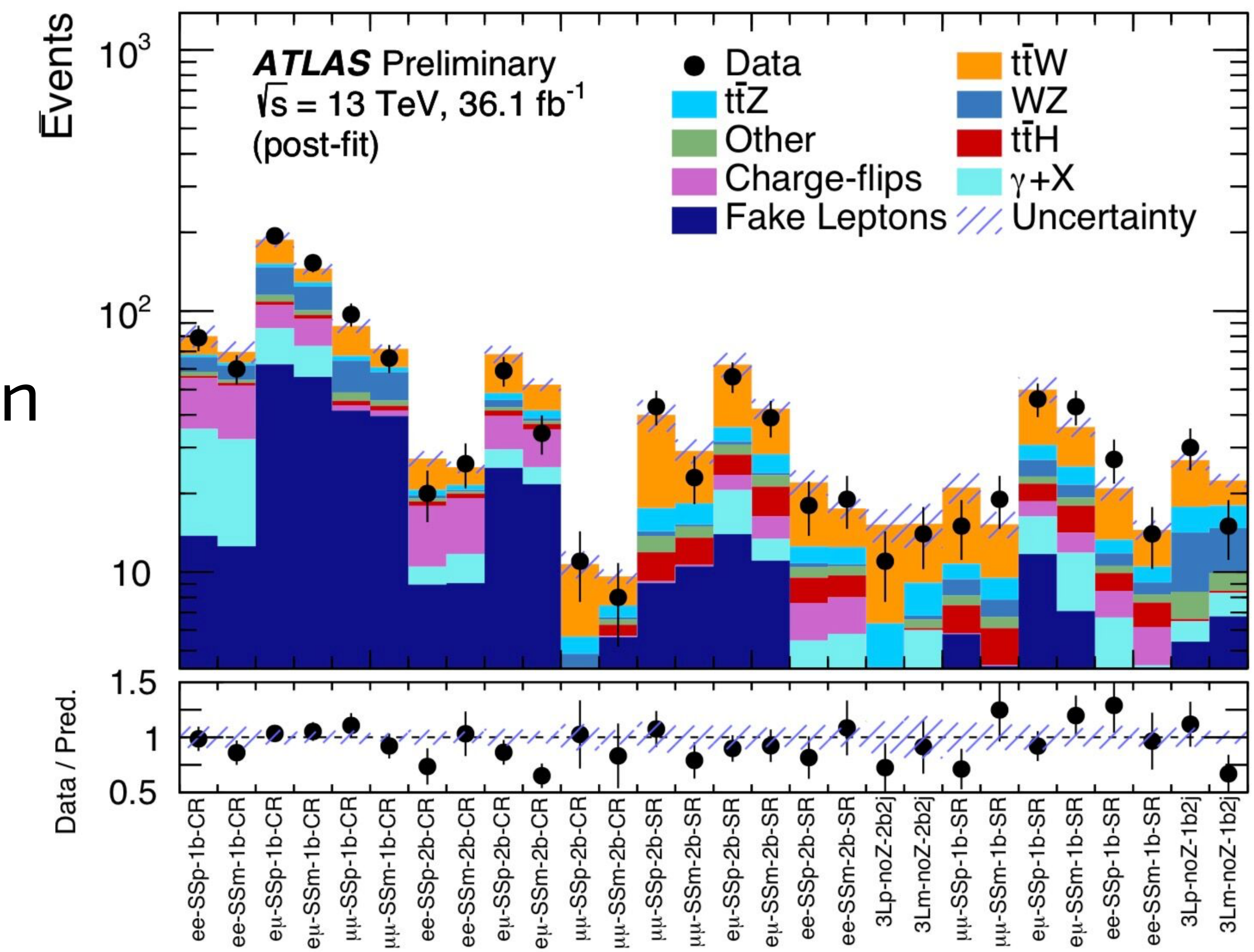
BACKUP - $t\bar{t}W$ analysis overview

2 analysis channels

- 2ℓSS: 12 signal regions & 12 control regions
  - Fake lepton background estimated with matrix method in the control regions
- 3ℓ: four signal regions

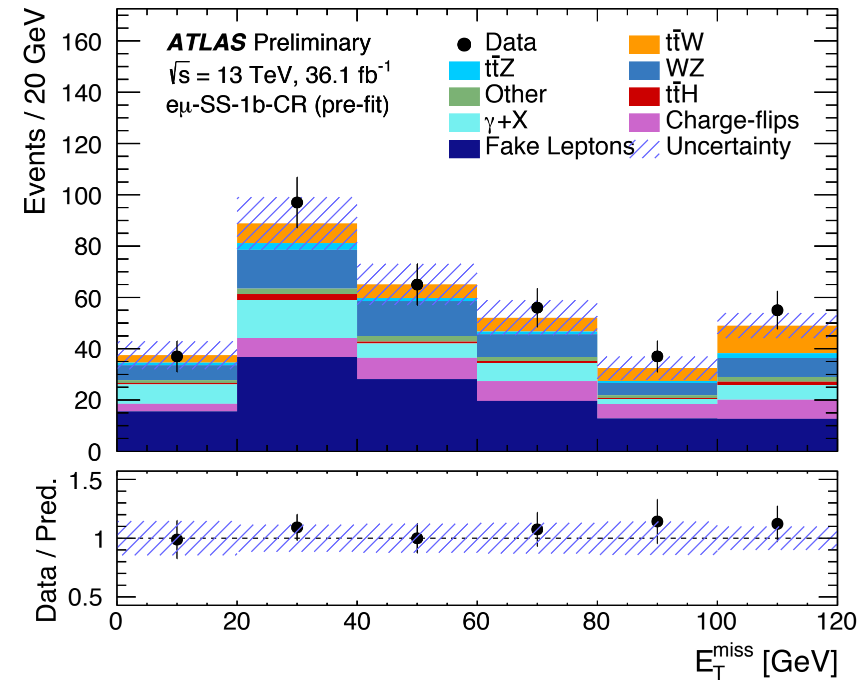
Fit parameters

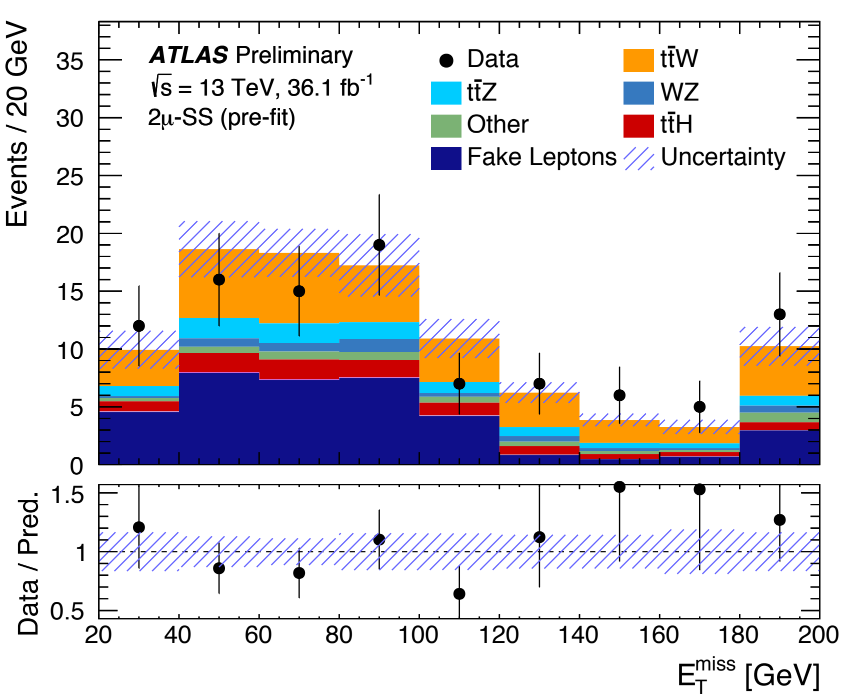
- $\mu(t\bar{t}W)$
- Signal contamination in fake lepton control regions
  - Anticorrelation of fake leptons with $\mu(t\bar{t}W)$

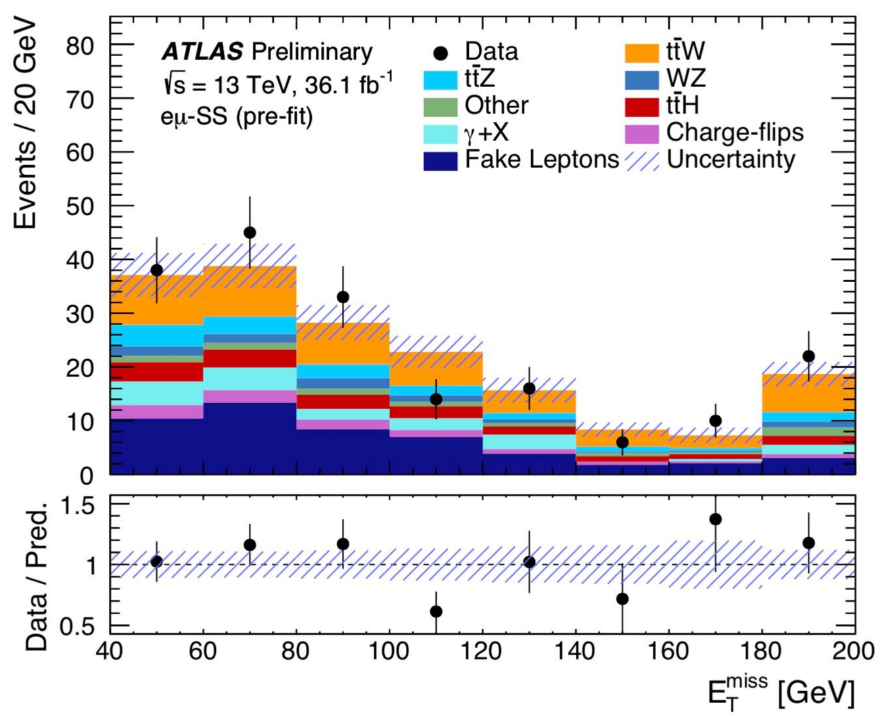


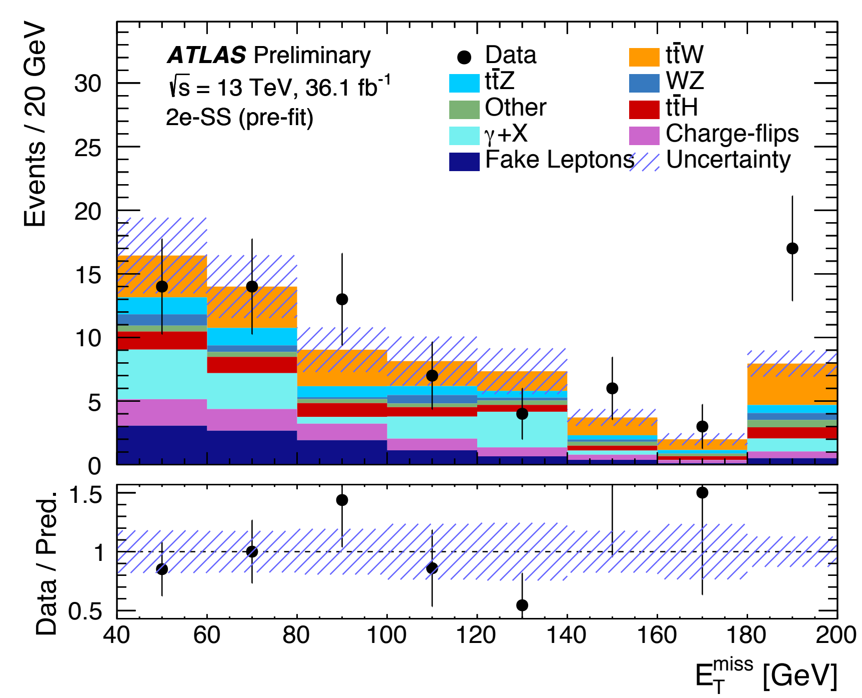
BACKUP - 2ℓSS $t\bar{t}W$

Requirement	l_1l_2-SS(p,m)-1b	2μ-SS(p,m)-2b	l_1l_2-SS(p,m)-2b
$n_{b-\text{jets}}$	=1	≥ 2	
E_T^{miss}	> 40 GeV	> 20 GeV	> 40 GeV
H_T		> 240 GeV	
p_T (leading lepton)		> 27 GeV	
p_T (subleading lepton)		> 27 GeV	
n_{jets}	≥ 4	≥ 2	≥ 4
Z-like lepton pair		vetoed in the $2e$ and 2μ regions	



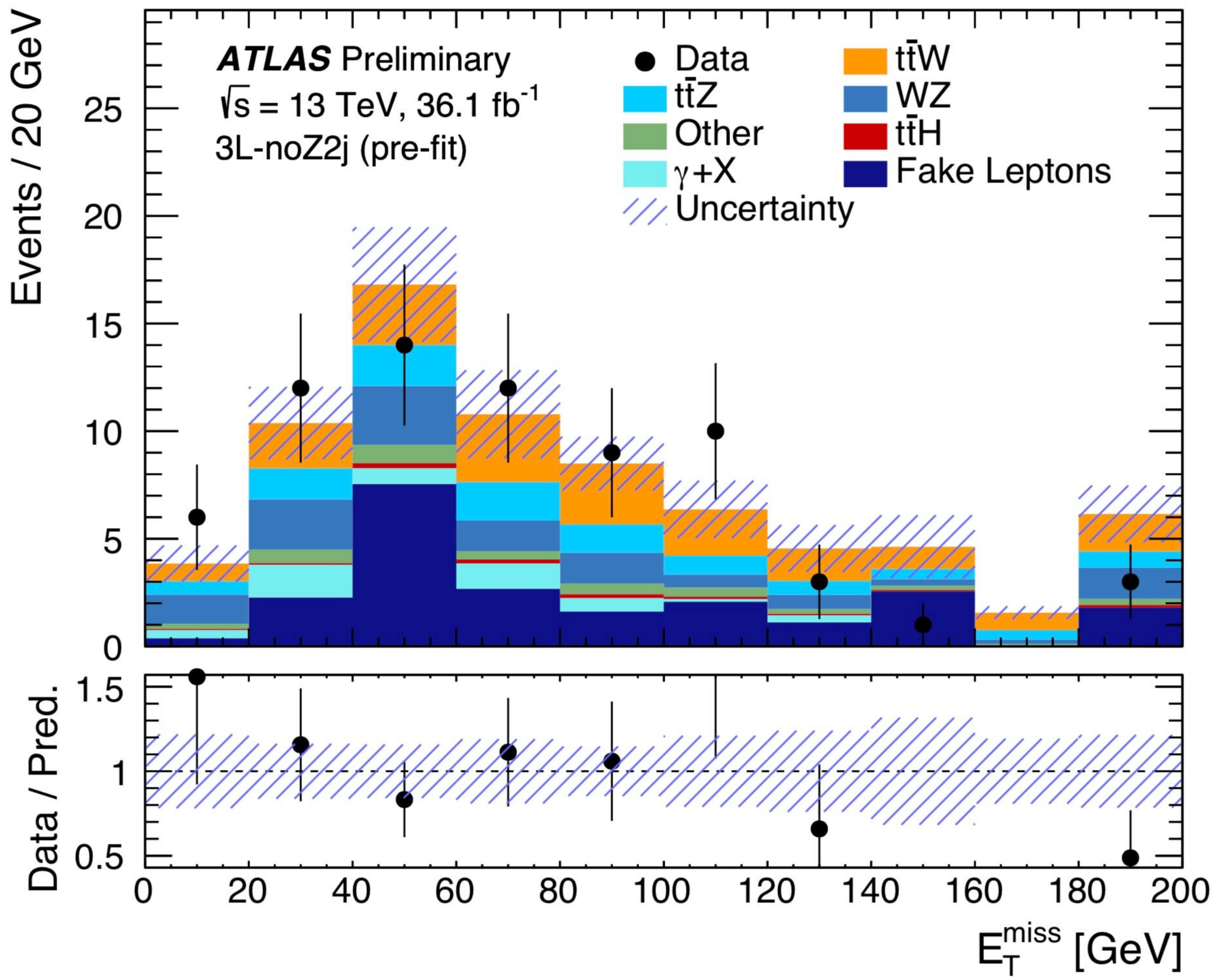






BACKUP - $3\ell\ t\bar{t}W$

Variable	3ℓp-noZ-2b2j	3ℓm-noZ-2b2j	3ℓp-noZ-1b2j	3ℓm-noZ-1b2j
All leptons	$p_T > 27$ GeV			
Z-like OSSF pair	vetoed			
n_{jets}	2 or 3			
H_T	-		> 240 GeV	
Sum of lepton charges	+1	-1	+1	-1
$n_{b-\text{jets}}$	≥ 2	≥ 2	1	1



BACKUP - 2ℓOS $t\bar{t}Z$

Variable	2ℓ-Z-6j1b	2ℓ-Z-5j2b	2ℓ-Z-6j2b
Leptons	= 2, same-flavor and opposite-sign		
$m_{\ell\ell}$	$\lvert m_{\ell\ell} - m_Z \rvert < 10$ GeV		
p_T (leading lepton)	>30 GeV		
p_T (subleading lepton)	>15 GeV		
$n_{b-\text{jets}}$	=1	≥ 2	≥ 2
n_{jets}	≥ 6	=5	≥ 6

Z+1HF

1.19 ± 0.25

Z+2HF

1.09 ± 0.13

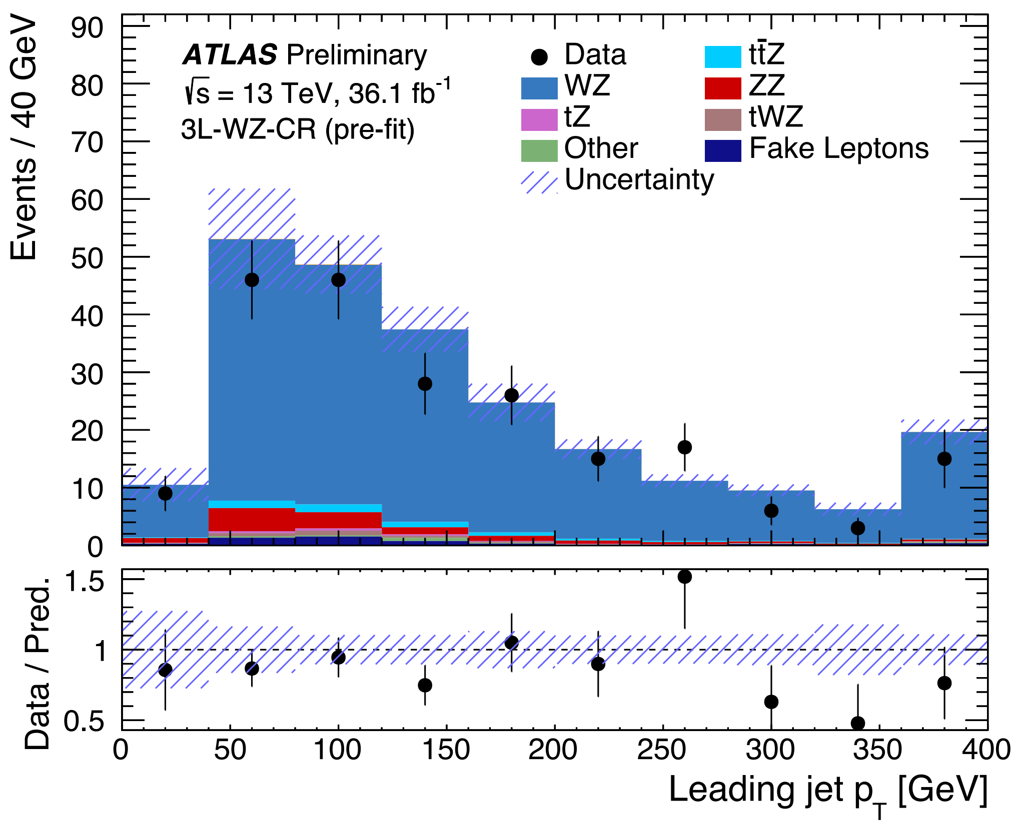
BACKUP - 2ℓOS $t\bar{t}Z$

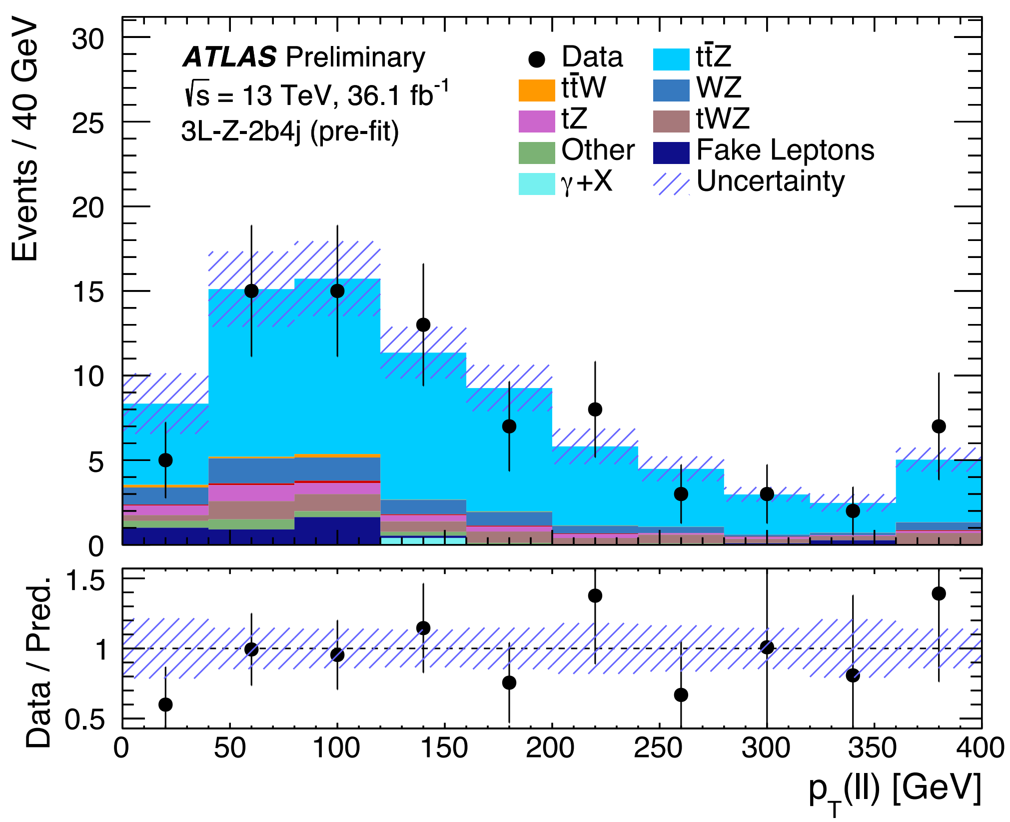
		Ranking		
Variable	Definition	6j1b	5j2b	6j2b
p_T^{ll}	p_T of the lepton pair	8	11	8
p_T^{4jet}	p_T of the fourth jet	6	12	6
p_T^{5jet}	p_T of the fifth jet	-	14	-
p_T^{6jet}	p_T of the sixth jet	9	-	11
ΔR_{ll}	ΔR between the two leptons	7	8	12
$N_{jetpairs}^{V mass}$	number of jet pairs with mass within a window of 30 GeV around 85 GeV	4	6	4
$N_{\mathrm{bjj}}^{\mathrm{top-mass}}$	number of 3 jets combinations (with exactly 1 b-tag jet) close to the top-quark mass ($\|M_{bjj} - M_{top}\| < 15$ GeV) and ($\|M_{jj} - M_W\| < 15$ GeV)	-	-	17
$M_{\mathrm{jj}}^{\mathrm{MindR}}$	mass of the combination between any two jets with the smallest ΔR	13	7	14
$M_{\mathrm{uu}}^{\mathrm{Ptord}}$	mass of the two untagged jets with the highest p_T	15	13	-
M_{bb}	mass of the two jets with the highest b-tag weight	-	10	9
$\mathrm{Cent}_{\mathrm{jet}}$	scalar sum of $\mathrm{p_T}$ divided by sum of E for all jets	2	1	2
$\Delta R_{\mathrm{ave}}^{\mathrm{jj}}$	average ΔR for all jet pairs	5	4	5
$\max M_{\mathrm{lepb}}^{\mathrm{MindR}}$	maximum mass between a lepton and the tagged jet with the smallest ΔR	14	-	13
$H1$	First Fox-Wolfram moment built from jets and leptons	3	2	1
H_T^{6jets}	sum of jet p_T, up to 6 jets	12	5	10
$\eta_{\ell\ell}$	η of dilepton system	1	3	3
M_W^{avg}	sum of the two closest 2 jet invariant masses from from $\mathrm{jjj_1}$ and $\mathrm{jjj_2}$ divided by 2.	10	-	15
ΔR_{bb}	cone between two jets with the highest b-tagging weight in the event	-	9	7
p_T^{b1}	p_T of the first b-jet. Jets are ordered according to the p_T	11	-	16

Variable	3ℓ-Z-1b4j	3ℓ-Z-2b3j	3ℓ-Z-2b4j	3ℓ-noZ-2b4j
Leading lepton	$p_T > 27$ GeV			
Other leptons	$p_T > 20$ GeV			
Sum of lepton charges	± 1			
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

WZ

0.91 ± 0.10





BACKUP - $t\bar{t}Z$ EFT parametrisation

$$\mathcal{L}^{\rm SM}_{t\bar{t}Z} = e\,\bar{u}(p_t)\left[\gamma^\mu\left(C_{\rm V}^{Z,\rm SM} + \gamma_5 C_{\rm A}^{Z,\rm SM}\right)\right]v(p_{\bar{t}})Z_\mu$$

($t\bar{t}Z$ SM Lagrangian)

$$C_{\rm V}^{Z,\rm SM} = \frac{T_t^3 - 2Q_t\sin^2\theta_w}{2\sin\theta_w\cos\theta_w} \approx 0.24, \qquad C_{\rm A}^{Z,\rm SM} = \frac{-T_t^3}{2\sin\theta_w\cos\theta_w} \approx -0.60$$

$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \frac{\mathcal{C}_i}{\Lambda}\mathcal{O}_{iD5} + \frac{\mathcal{C}_i}{\Lambda^2}\mathcal{O}_{iD6} + \frac{\mathcal{C}_i}{\Lambda^3}\mathcal{O}_{iD7} + \frac{\mathcal{C}_i}{\Lambda^4}\mathcal{O}_{iD8} + \ldots$$

(general EFT Lagrangian)

[JHEP 08 (2015) 044]

$$\mathcal{L}_{t\bar{t}Z} = e\bar{u}(p_t)\left[\gamma^\mu\left(C^Z_{1,V} + \gamma_5 C^Z_{1,A}\right) + \frac{\mathrm{i}\sigma^{\mu\nu}q_\nu}{M_Z}\left(C^Z_{2,V} + \mathrm{i}\gamma_5 C^Z_{2,A}\right)\right]v(p_{\bar{t}})Z_\mu$$

$t\bar{t}Z$ anomalous dipole moments extension

$$\begin{aligned}
O^{(3)}_{\varphi Q} &= i\frac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}^I_\mu \varphi\right)\left(\bar{Q}\gamma^\mu\tau^I Q\right)\\
O^{(1)}_{\varphi Q} &= i\frac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)\left(\bar{Q}\gamma^\mu Q\right)\\
O_{\varphi t} &= i\frac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)\left(\bar{t}\gamma^\mu t\right)\\
O_{tW} &= y_t g_w(\bar{Q}\sigma^{\mu\nu}\tau^I t)\tilde{\varphi}W^I_{\mu\nu}\\
O_{tB} &= y_t g_Y(\bar{Q}\sigma^{\mu\nu} t)\tilde{\varphi}B_{\mu\nu}\\
O_{tG} &= y_t g_s(\bar{Q}\sigma^{\mu\nu}T^A t)\tilde{\varphi}G^A_{\mu\nu}\,.
\end{aligned}$$

$$\begin{aligned}
C^Z_{1,V} &= \frac{1}{2}\left(C^{(3)}_{\varphi Q} - C^{(1)}_{\varphi Q} - C_{\varphi t}\right)\frac{m_t^2}{\Lambda^2 s_W c_W}\\
C^Z_{1,A} &= \frac{1}{2}\left(-C^{(3)}_{\varphi Q} + C^{(1)}_{\varphi Q} - C_{\varphi t}\right)\frac{m_t^2}{\Lambda^2 s_W c_W}\\
C^Z_{2,V} &= \left(C_{tW}c_W^2 - C_{tB}s_W^2\right)\frac{2m_t m_Z}{\Lambda^2 s_W c_W}\\
C^Z_{2,A} &= 0
\end{aligned}$$

[PhD thesis, Olga B.]

BACKUP - EFT interpretation

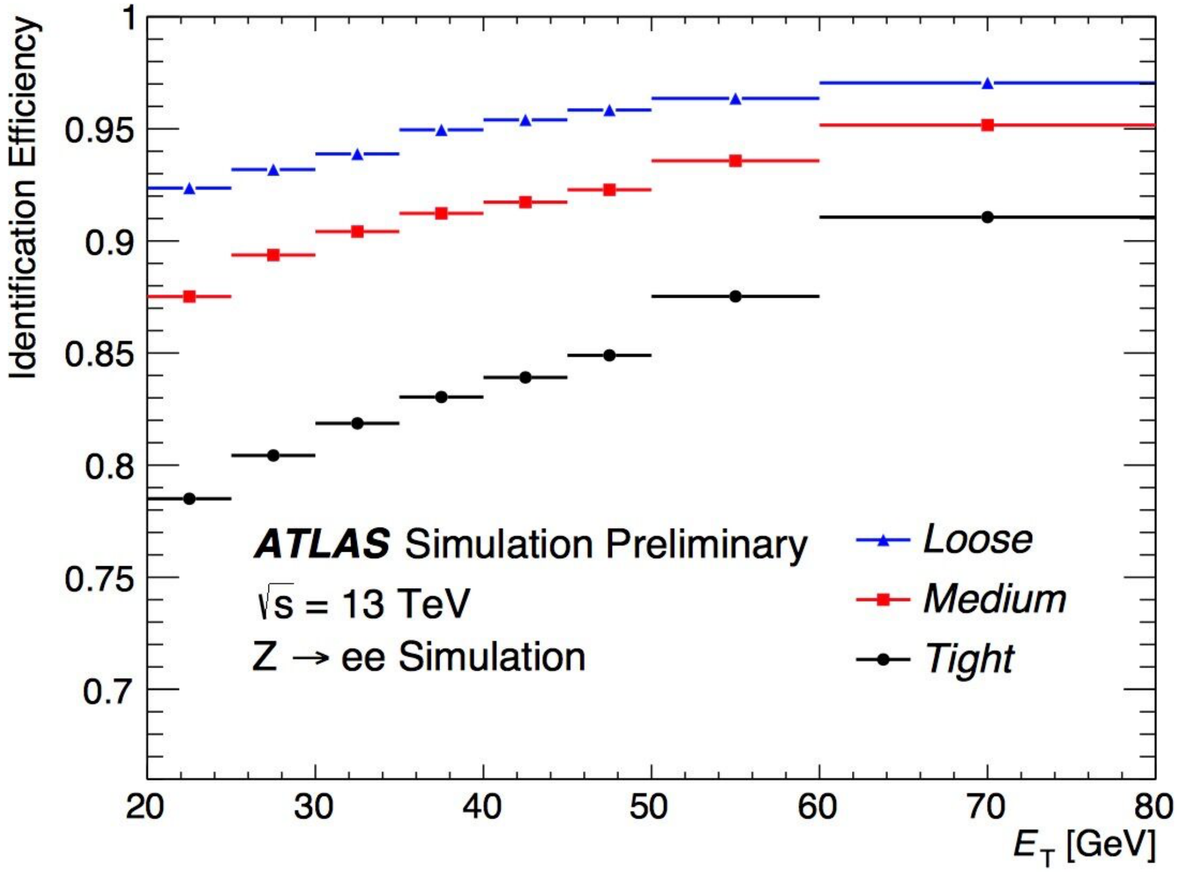
UNIVERSITÄT BONN

Interpretation

- Perform fit to extract C_i/Λ^2
  - one operator at a time
- Able to match or improve previous CL

Coefficient	Expected limits at 68% and 95 % CL	Observed limits at 68% and 95 % CL	Previous constraints at 95 % CL
$(C_{\phi Q}^{(3)} - C_{\phi Q}^{(1)})/\Lambda^2$	[-2.1, 1.9], [-4.6, 3.7]	[-1.0, 2.7], [-3.4, 4.3]	[-3.4, 7.5]
$C_{\phi t}/\Lambda^2$	[-3.8, 2.8], [-23, 5.0]	[-2.0, 3.6], [-27, 5.7]	[-2.0, 5.7]
C_{tB}/Λ^2	[-8.3, 8.6], [-12, 13]	[-11, 10], [-15, 15]	[-16, 43]
C_{tW}/Λ^2	[-2.8, 2.8], [-4.0, 4.1]	[-2.2, 2.5], [-3.6, 3.8]	[-0.15, 1.9]

BACKUP - Leptons in ATLAS



ATLAS-CONF-2016-024
electrons

	$4 < p_T < 20$ GeV		$20 < p_T < 100$ GeV	
Selection	ϵ_μ^{MC} [%]	$\epsilon_{Hadrons}^{MC}$ [%]	ϵ_μ^{MC} [%]	$\epsilon_{Hadrons}^{MC}$ [%]
Loose	96.7	0.53	98.1	0.76
Medium	95.5	0.38	96.1	0.17
Tight	89.9	0.19	91.8	0.11
High-p_T	78.1	0.26	80.4	0.13

muons
EPJC 76 (2016) 292

Table 1: Efficiency for prompt muons from W decays and hadrons decaying in flight and misidentified as prompt muons computed using a $t\bar{t}$ MC sample. The results are shown for the four identification selection criteria separating low ($4 < p_T < 20$ GeV) and high ($20 < p_T < 100$ GeV) momentum muons for candidates with $|\eta| < 2.5$. The statistical uncertainties are negligible.