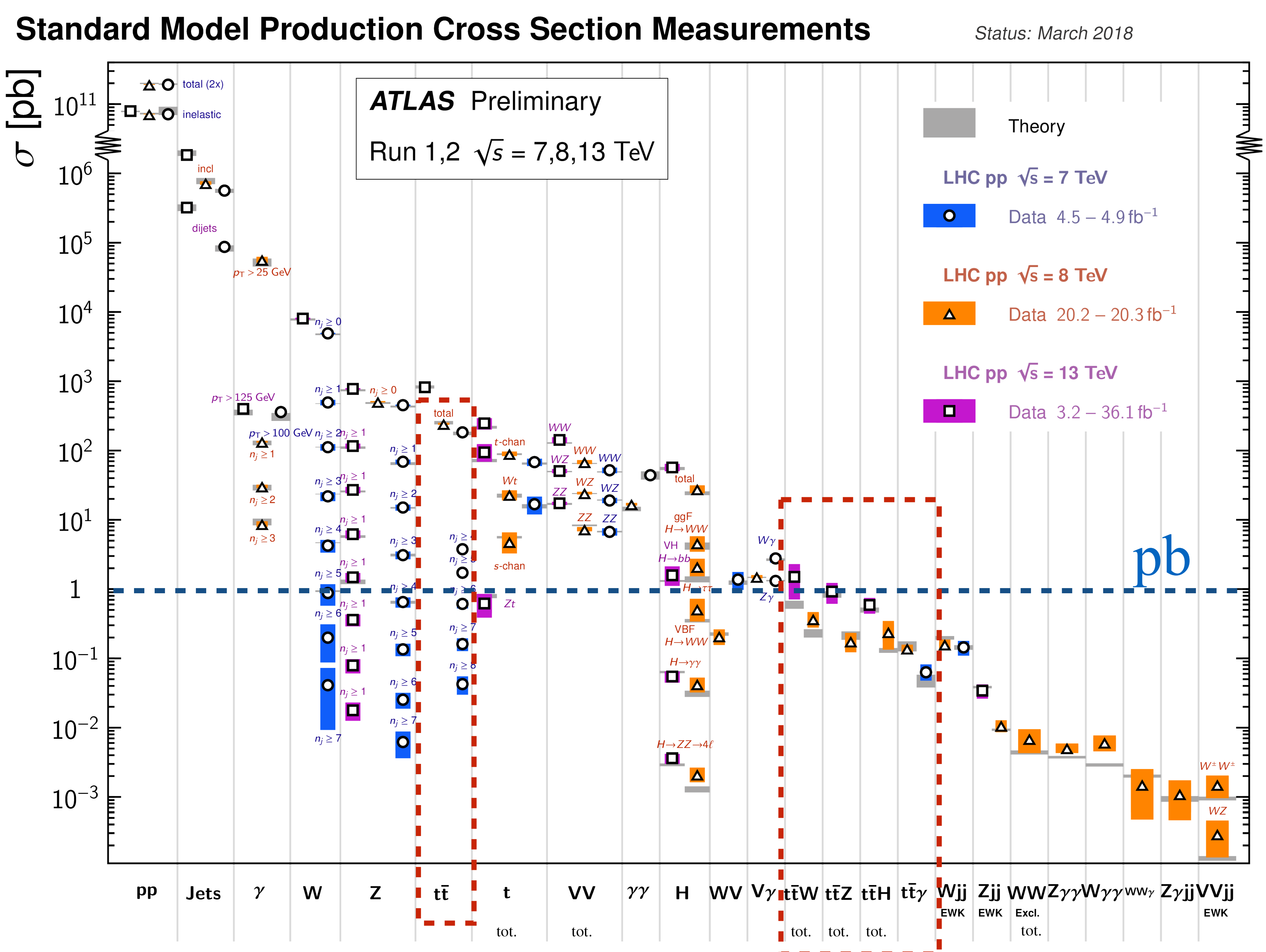
Measurements of $t\bar{t}$ +X using the ATLAS detector

Hasib Ahmed

Introduction

Large statistics and increased center-of-mass energy allows access to the phase space for $t\bar{t}$ associated production at the LHC

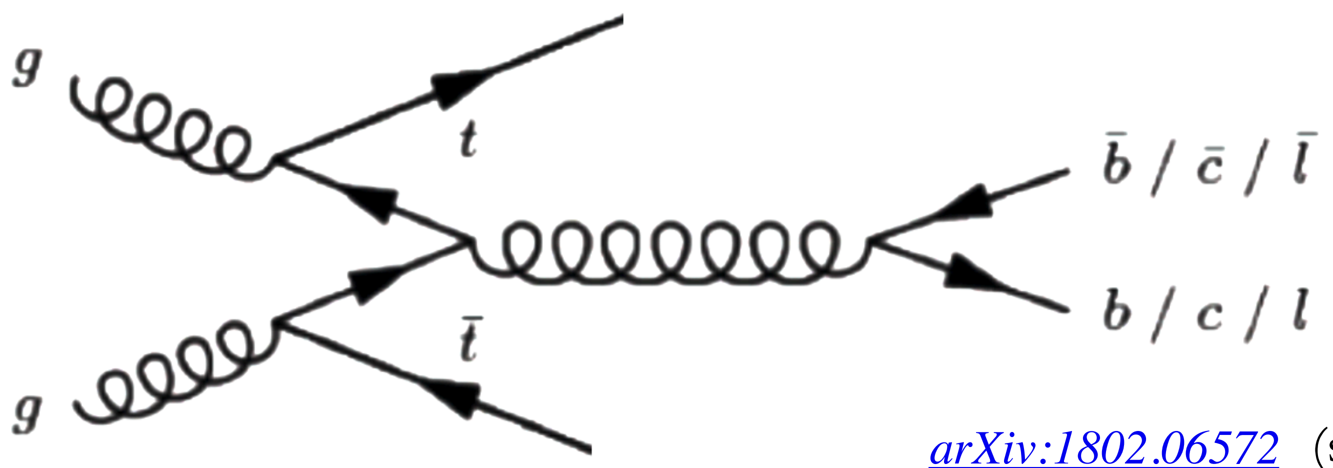


✓ $t\bar{t}$ +*jets* @ 13TeV
✓ $t\bar{t}$+W/Z @ 13TeV
✓ $t\bar{t}$ +γ @ 8 TeV

$t\bar{t}$ +*H*: **see talk by Arthur Chomont at the Higgs+BSM (WG1) session**

$t\bar{t}$+jets @ 13TeV: 3.2 fb^{-1}

- Sensitive to initial/final state radiation (ISR/FSR) and modeling of $t\bar{t}$ production
- Important test of pQCD and Standard Model (SM)
- Improve modeling of parton shower and hadronization
- Dominant background for several beyond SM searches



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arXiv:1802.06572 (submitted to *JHEP*):

❖ Measurement of additional jet activity produced in electron + muon $t\bar{t}$ events:
- $1e^{\pm}$ and $1\mu^{\mp}$, ≥ 2 b-tag jets

Study additional jet multiplicity and additional jet-p_T spectra

❖ Measurement of $t\bar{t}$+jets differential cross section in electron or muon events
- 1e or 1μ, ≥ 4 jets (≥ 2 b-tag)

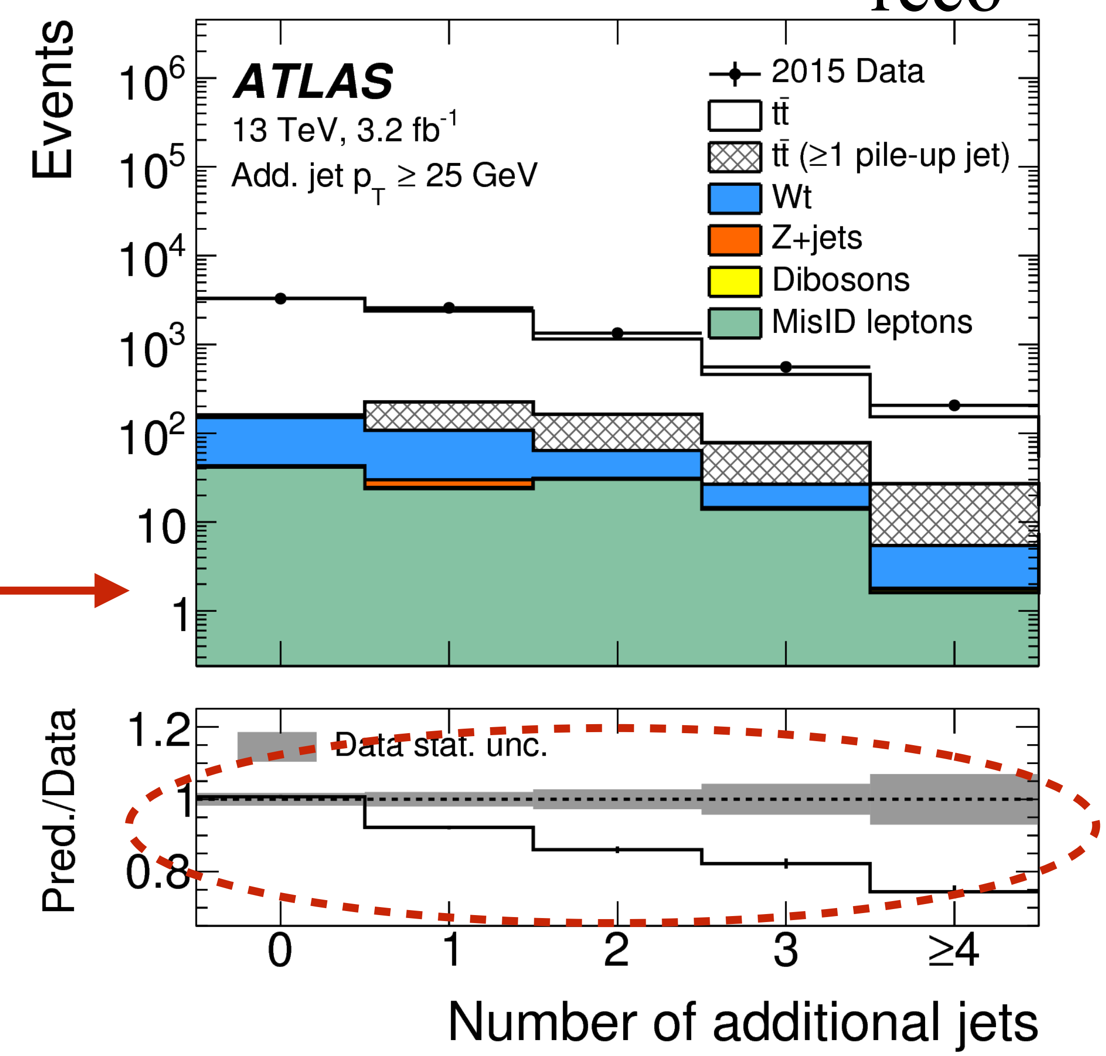
Reconstruct both top quarks and study $p_T(t^{had})$, $p_T(t\bar{t})$ in different n-jet bins

Additional jet activity in *eμ+2bjets* events

- Clean signature and small uncertainties
- Backgrounds ~ 4.5%
- Additional jets p_T thresholds of 25, 40, 60 and 80 GeV
- ~25% discrepancy in jet multiplicity at the reconstruction level
- Unfold to particle level

Background	Estimation
Single top (Wt) ~ 3.1%	Simulation normalized to predicted x-sec
Fake leptons ~ 1.6%	Data driven
Z+jets < 1%	Shape in simulation with normalization data driven
Diboson < 1%	Simulation

reco



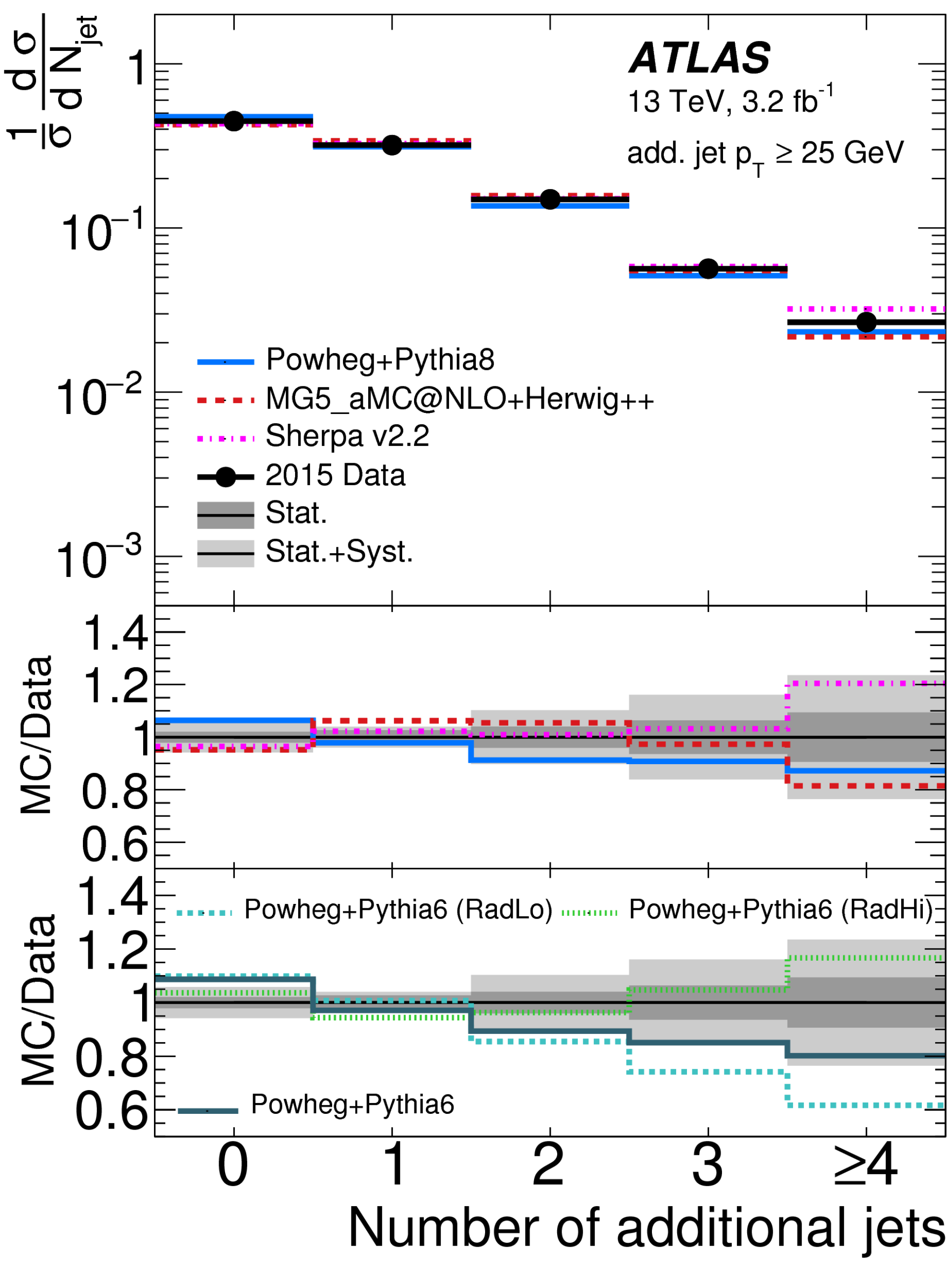
eμ events: jet multiplicities

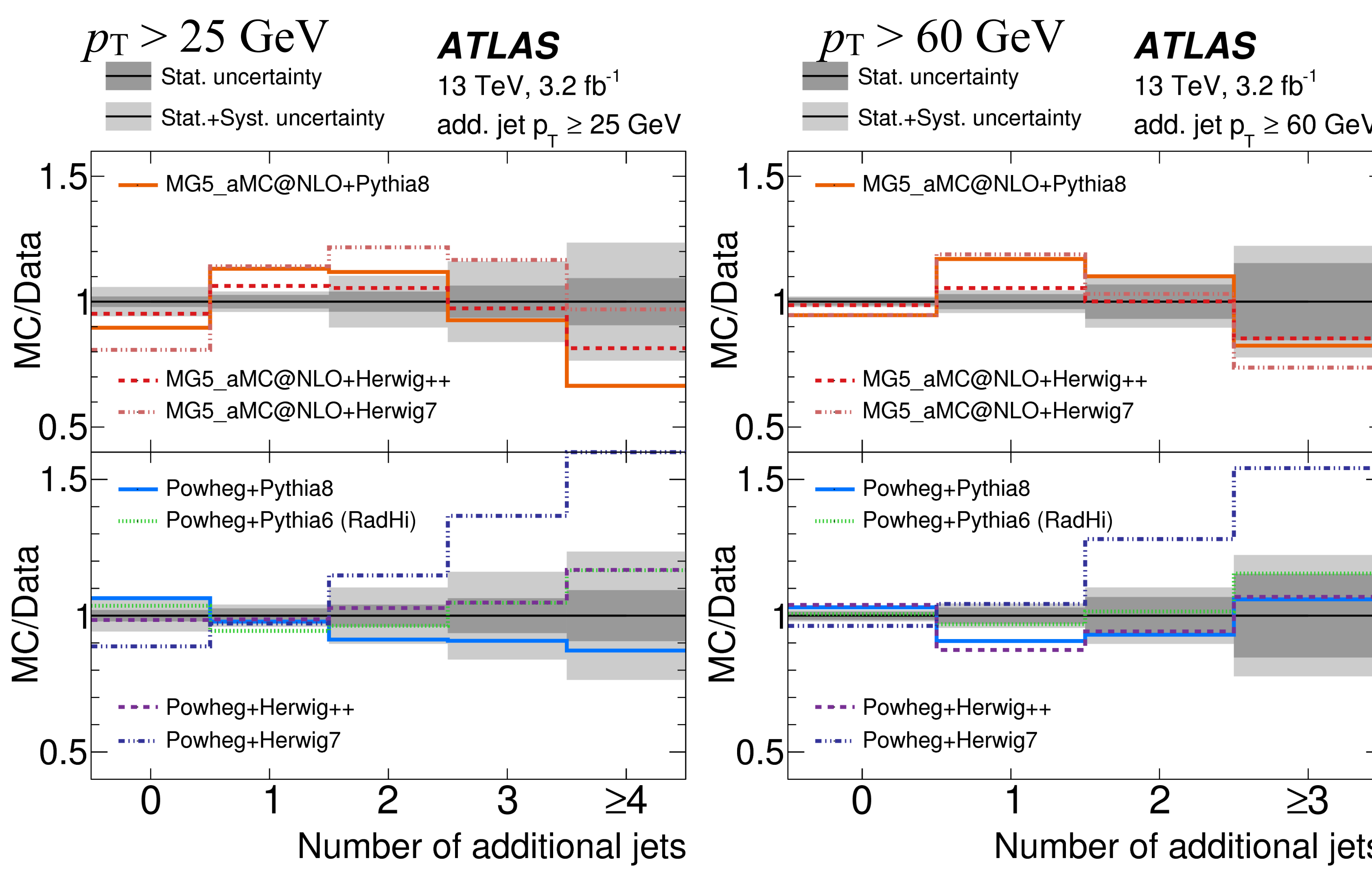
- Major systematic uncertainties:
  - jet energy scale (JES)
  - matrix element (ME), parton shower (PS), ISR/FSR
- Sensitive to ME, PS and scale variation

MG5_aMC@LO, Powheg varies 5-10% but within the uncertainty for all PS except Herwig7

Herwig7 deviates significantly for all pT threshold

$p_T > 25$ GeV

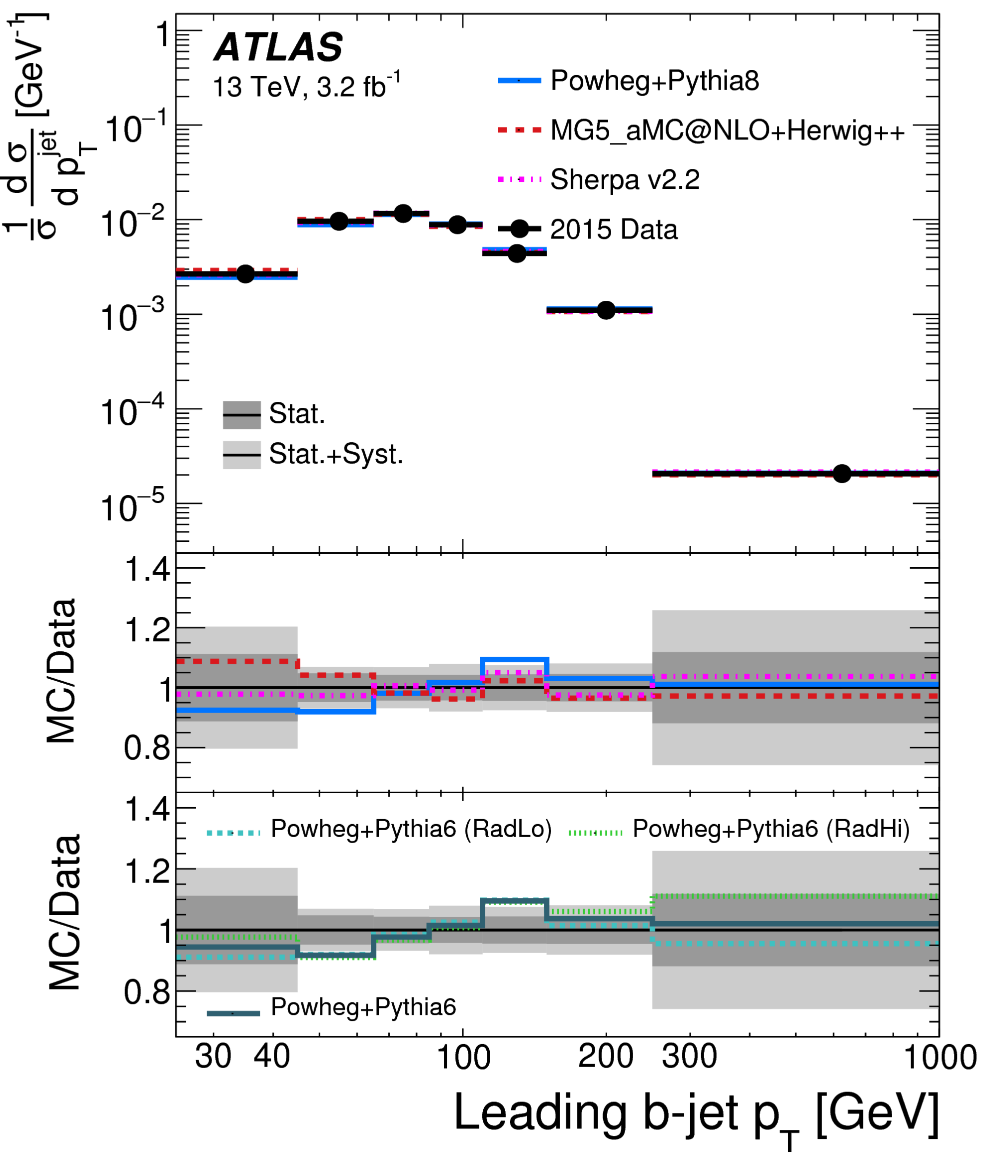


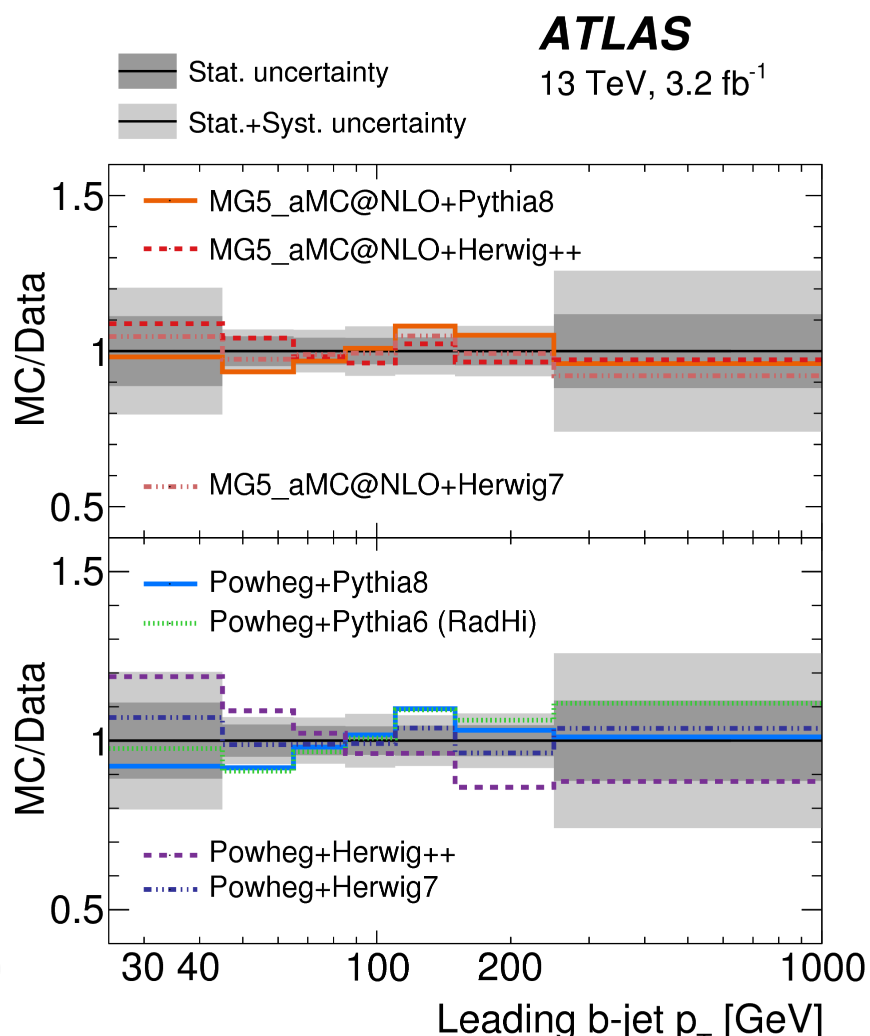


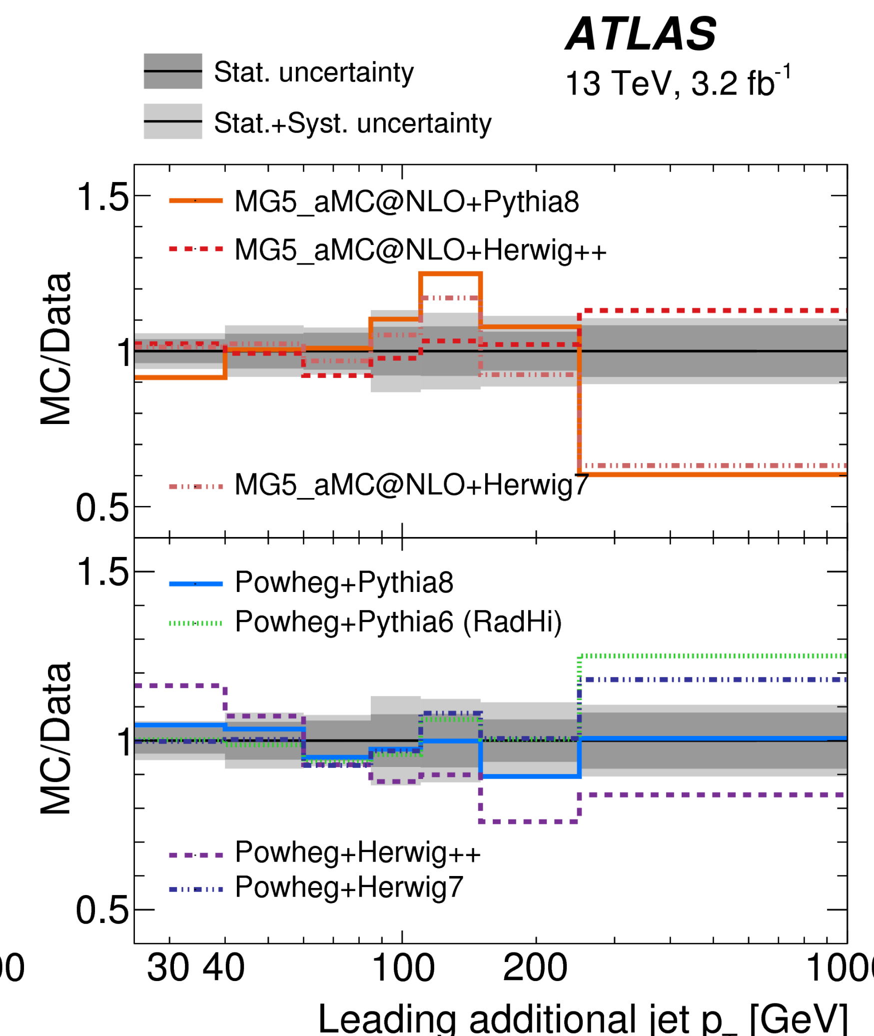
eμ events: additional jet p_T

- Normalized differential cross section:
  - additional leading jet/b-jet p_T
  - compare various and ME and PS models
- Major systematic uncertainties:
  - JES/JER
  - NLO generator
  - PS/hadronization

Powheg+Herwig++
MG5_aMC@LO+Pythia8
doesn't provide good description







$t\bar{t}$+*jets* in *e/μ+jets* events

- Sensitive to the effect of gluon radiation on the kinematic variables of $t\bar{t}$ production

- Analysis divided into 4-jet excl., 5-jet excl., 6-jet incl. regions

- Reconstruct the top quarks for $p_T(t^{had})$ and $p_T(t\bar{t})$

Background	**Estimation**
Single top ~ 5%	Simulation and normalized to predicted cross section
Multijet ~ 4%	Data driven
W+jets ~ 2 - 3%	Shape in simulation, normalization of heavy flavor fraction from data
Z+jets, $t\bar{t}$ *V, VV* ~ 1- 2%	Simulation and normalized to predicted cross sections.

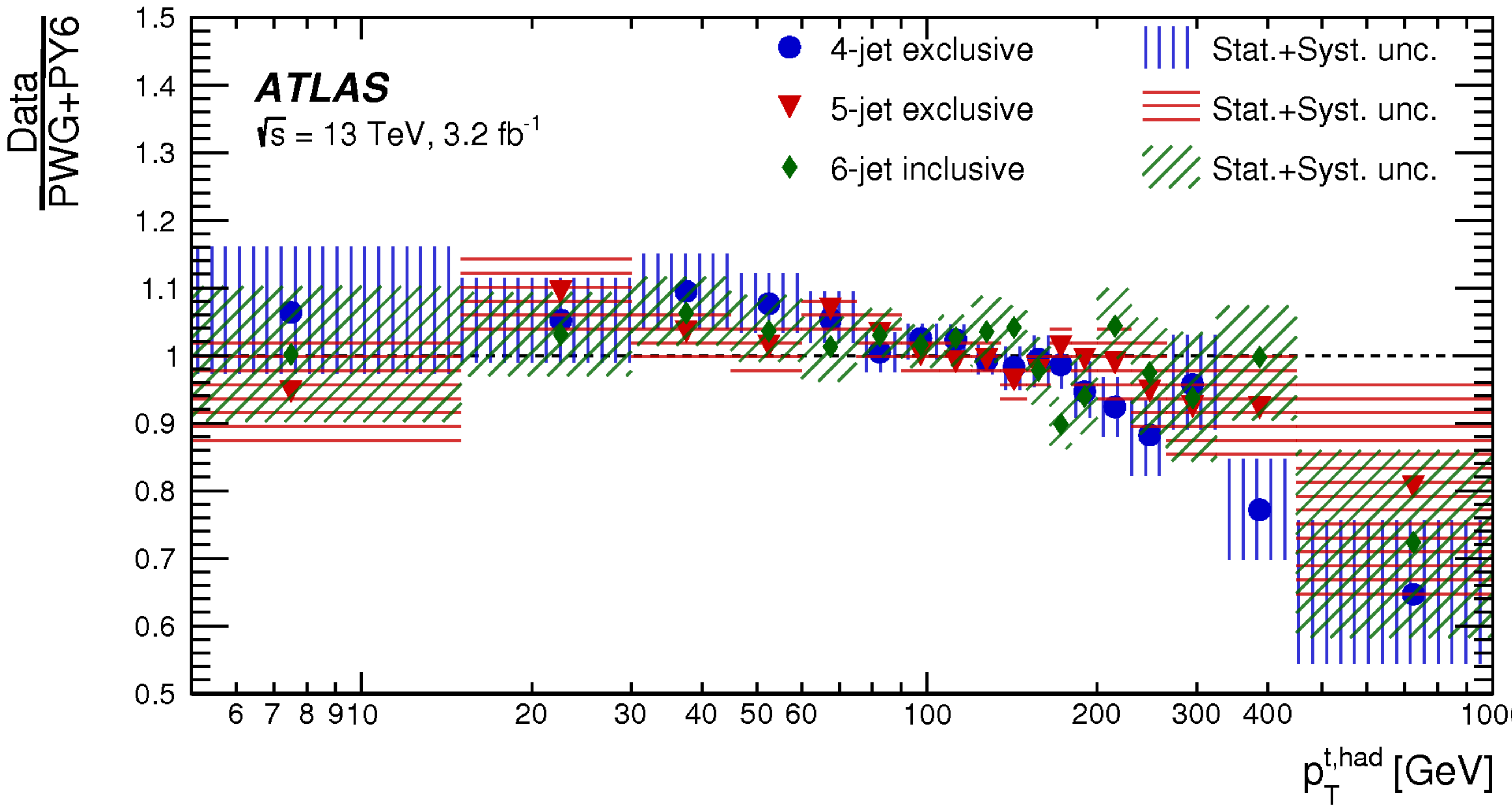
- The distributions are unfolded to particle level

e/μ+jets events: $p_T(t^{had})$ spectra

- Dominant uncertainties:
  - flavor tagging (4-jet excl.)
  - JES/JER increasing with jet multiplicity

- Models underestimate (overestimate) the data at low (high) values
- Agreement increases with jet multiplicity

Powheg+Herwig++ is found to be incompatible with data in χ2 test

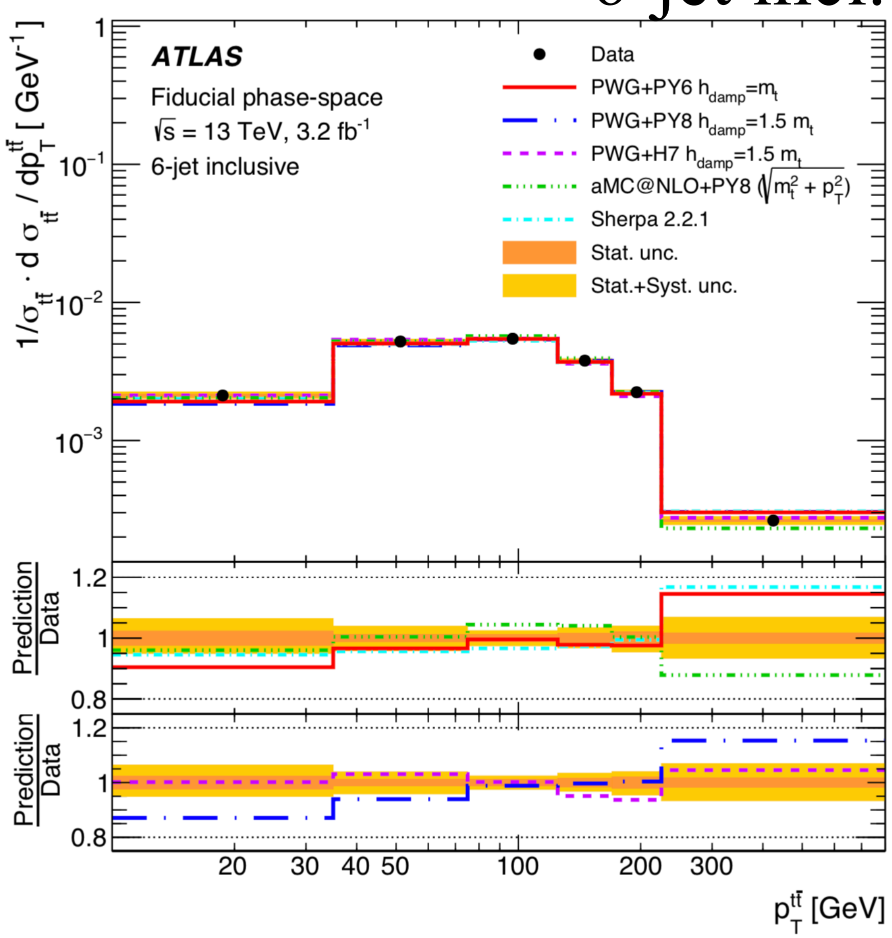


e/μ+jets events: $p_T(t\bar{t})$ spectra

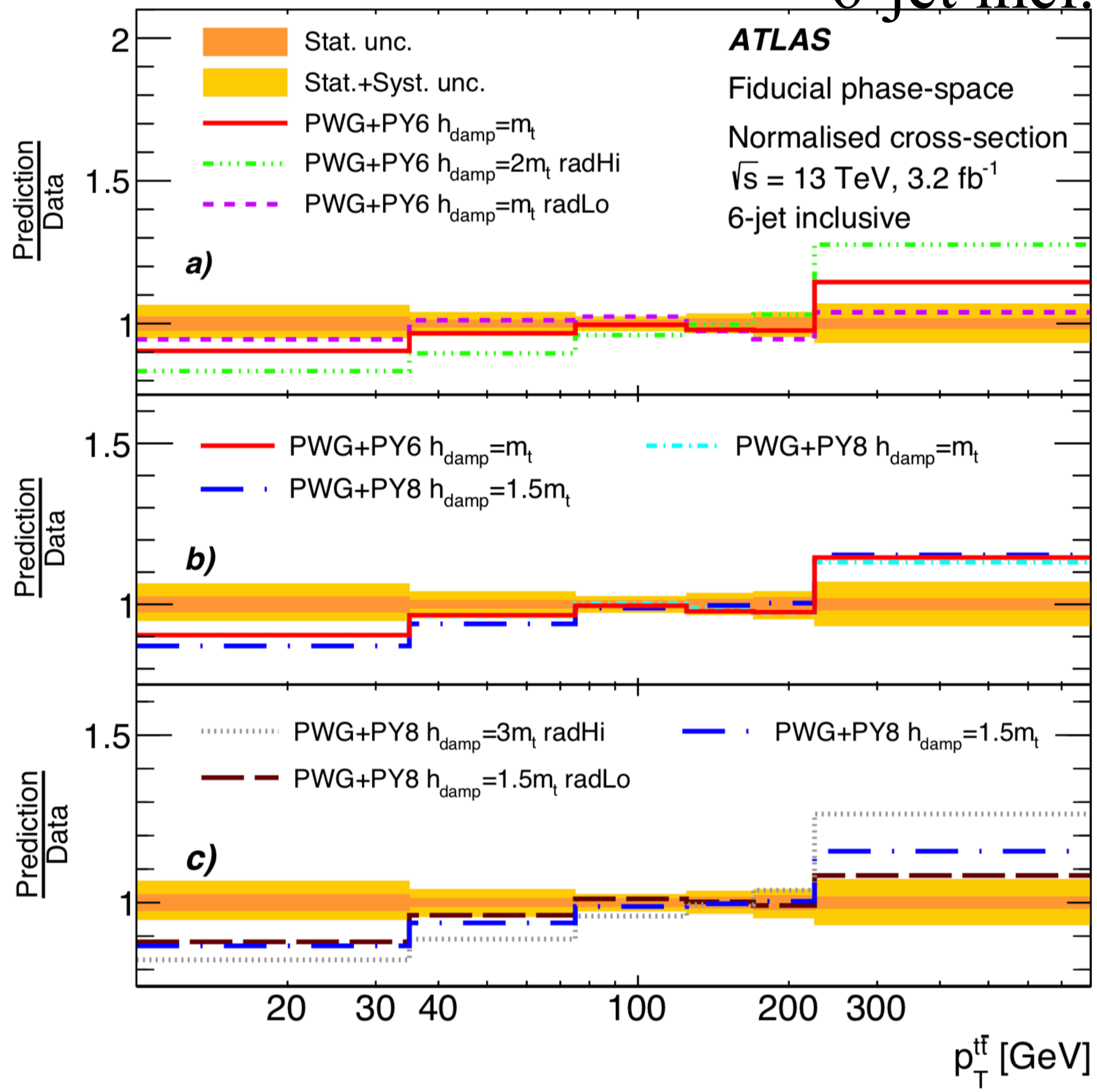
- Strongly sensitive to gluon emission:
  - increasing $p_T(t\bar{t})$ with increasing jet multiplicity
- Good agreement in 4-jet/5-jet region
- Some discrepancy in 6-jet incl.

MG5_aMC@NLO is found to be incompatible with data in χ2 test

6-jet incl.



6-jet incl.



$t\bar{t}+V(W/Z)$ @ 13TeV: 3.2 fb^{-1}

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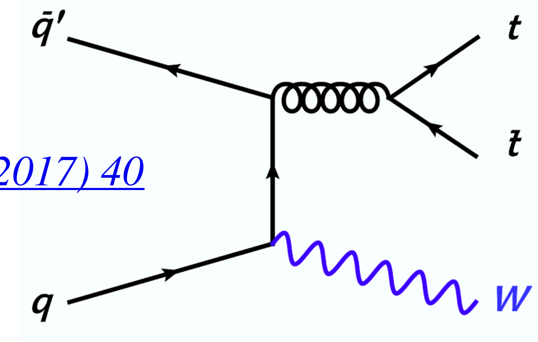
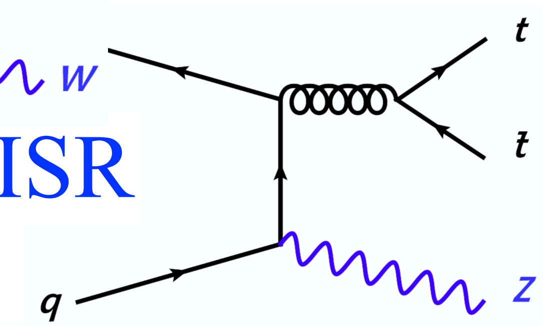
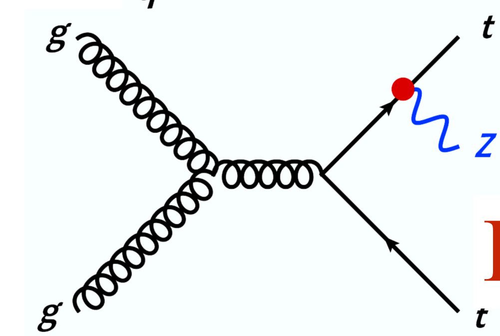




ISR



FSR

- Direct measurement of tZ coupling via FSR
- BSM models could enhance the $t\bar{t}+V$ cross section
- Dominant and irreducible background for many searches including $t\bar{t}+H$ production

Divide to multiple regions for maximum sensitivity

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

* same electric charge

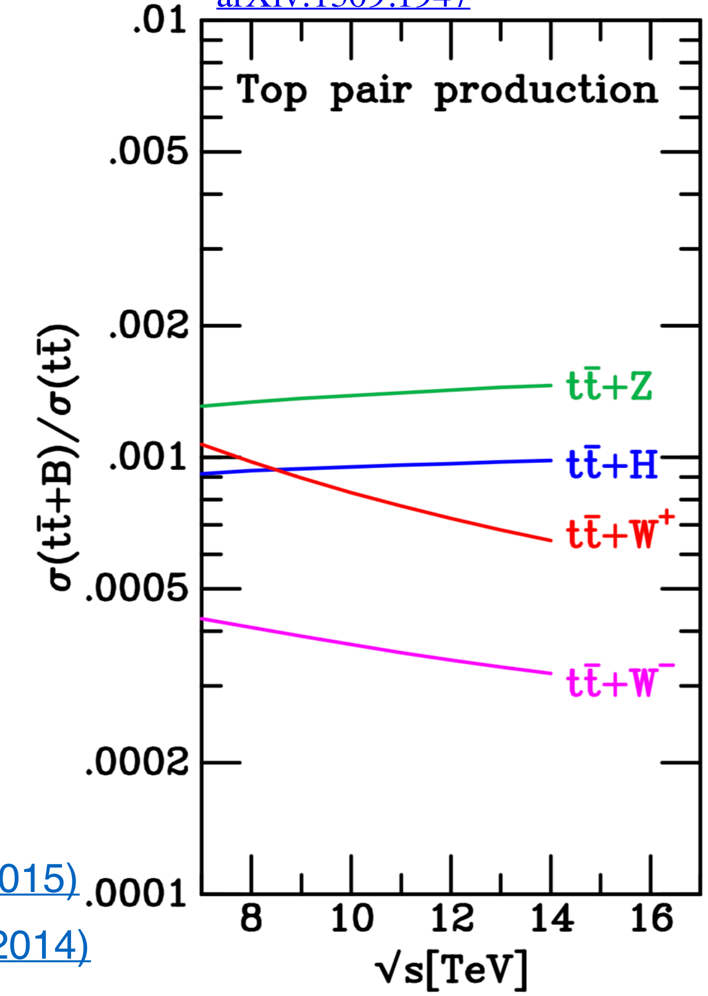
Simultaneous fit to the signal region (SR) and control regions (CR) to extract the $t\bar{t}+W/Z$ cross sections

NLO QCD predictions:

$$\sigma(t\bar{t}Z) = 0.84 \pm 0.09\ (\sim 11\%)\ \text{pb}$$
$$\sigma(t\bar{t}W) = 0.60 \pm 0.08\ (\sim 13\%)\ \text{pb}$$

JHEP 06,184 (2015)
JHEP 07, 079 (2014)

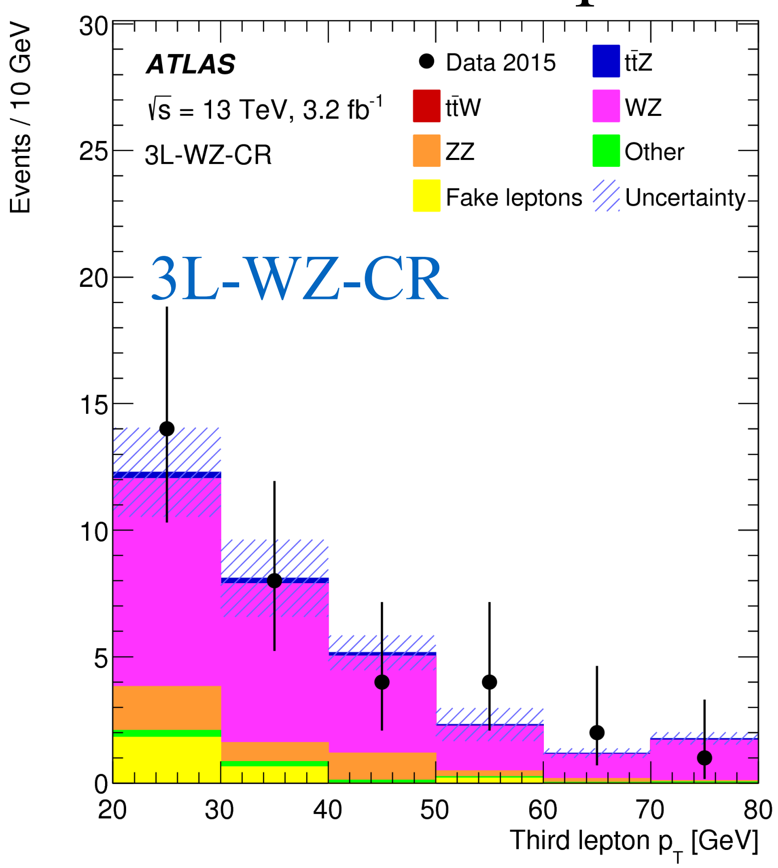
arXiv:1309.1947



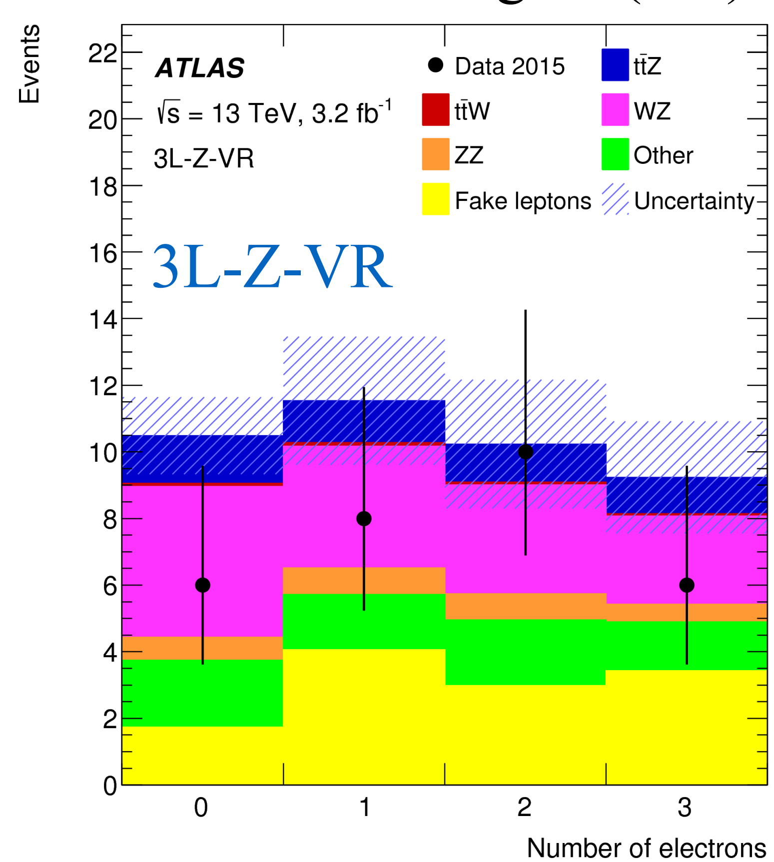
$t\bar{t}+Z$: 3-lepton and 4-lepton

	Selection	Main backgrounds
3lZ	• *Z* mass window < 10 GeV, • Pair of opposite electric charge but same flavor (OSSF) leptons • Separate: 1b4j, 2b3j, 2b4j regions	• **Fake leptons:** data driven Matrix method • ***WZ*:** shape in simulation with normalization from fit to data in a control region (3L-WZ-CR)
4l	• 2 pairs of OS leptons with at least 1 pair SF • Reconstruct two *Z* bosons • Separate by flavor: SF, DF(different flavor) • Separate: 4*l*-DF-1b, 4*l*-DF-2b, 4*l*-SF-1b, 4*l*-SF-2b	• ***ZZ*:** shape in simulation with normalization from fit to data in a control region (4L-ZZ-CR)

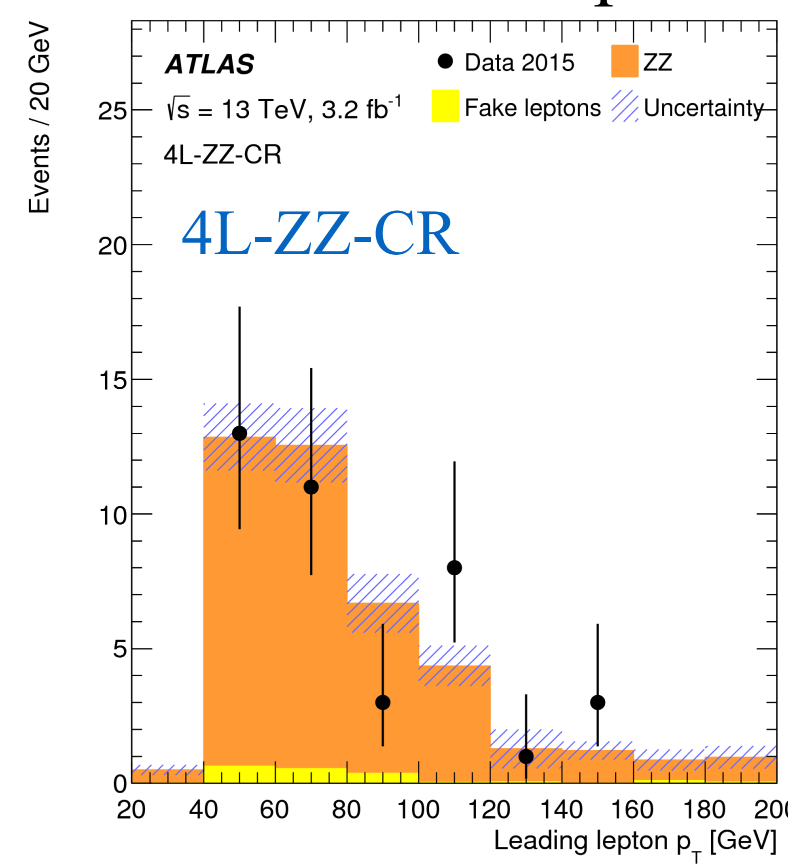
prefit



Validation Region (VR)



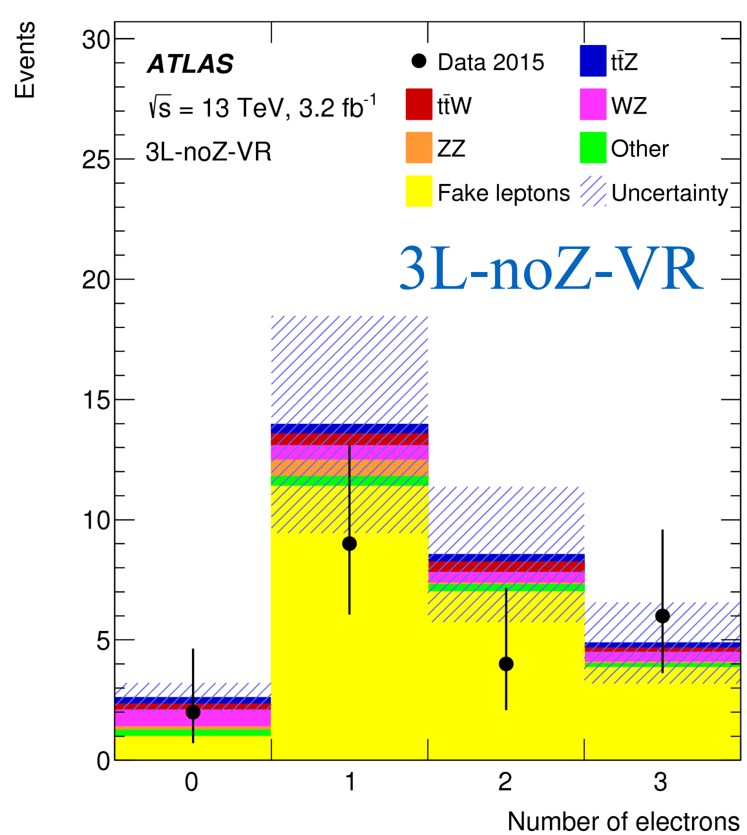
prefit

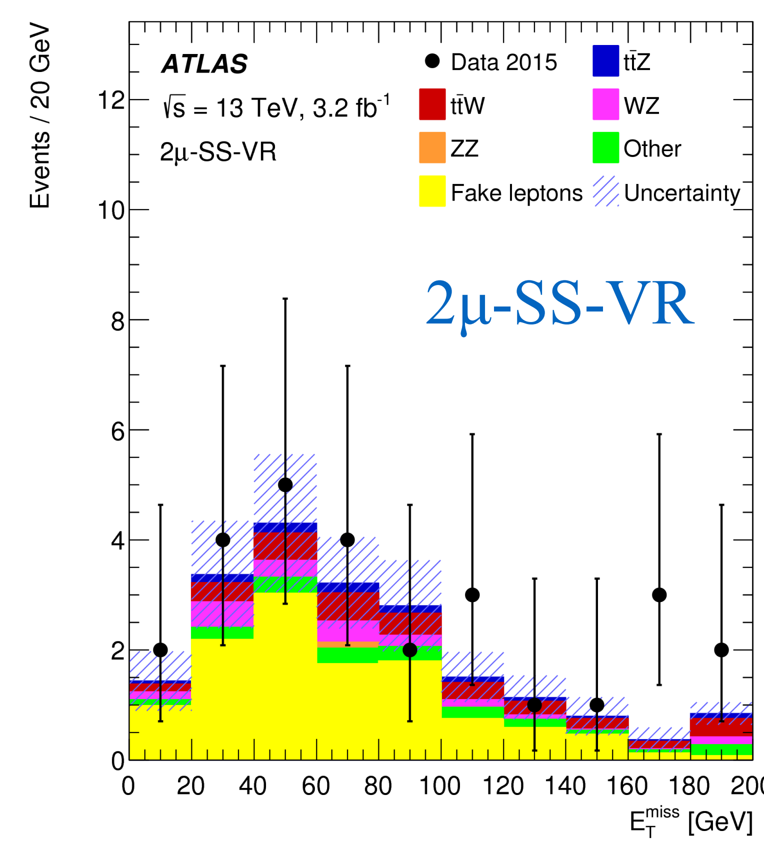


$t\bar{t}+W$: SS 2μ and 3L-no$Z$

	Selection	Main backgrounds
3*l* noZ	• *Z* mass window > 10 GeV (*Z* veto) • Sum of lepton electric charge ±1 • $2 \leq n_{\text{jets}} \leq 4$, $n_{\text{bjets}} \geq 2$	• $t\bar{t}$ **+*Z* :** simultaneous fit • $t\bar{t}$**+*H* :** simulation • **Fake leptons:** data driven Matrix method
2*μ*	• 2 muons with same electric charge (SS) • Sum of muon electric charge ±2 • Scalar sum of the p_{T} of μ+*jets*, $H_{\text{T}} > 240$ GeV • Missing transverse momentum, E_{T}(miss) > 20 GeV	• **Fake leptons:** data driven Matrix method

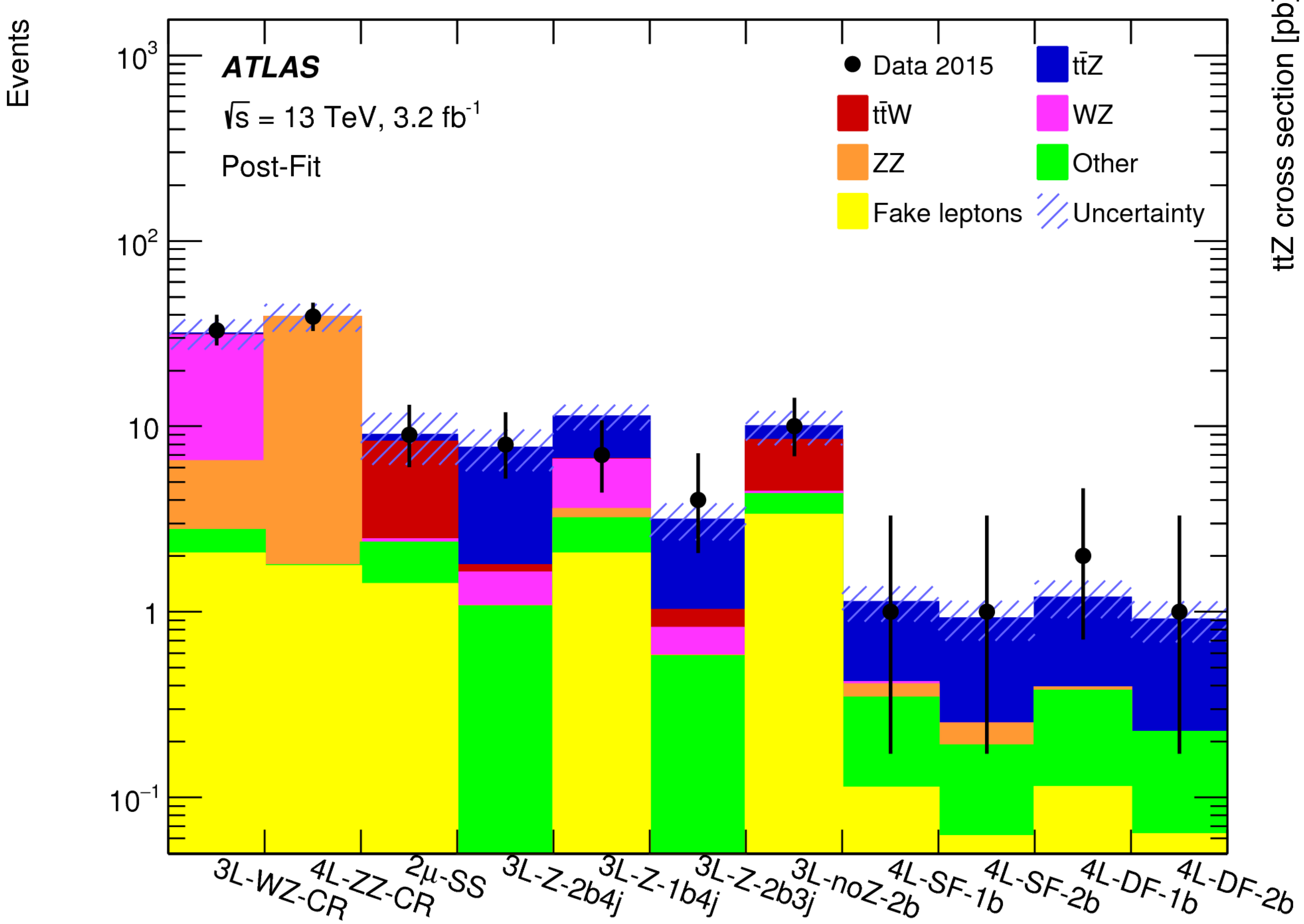
Validation regions (VR) to test the background estimations

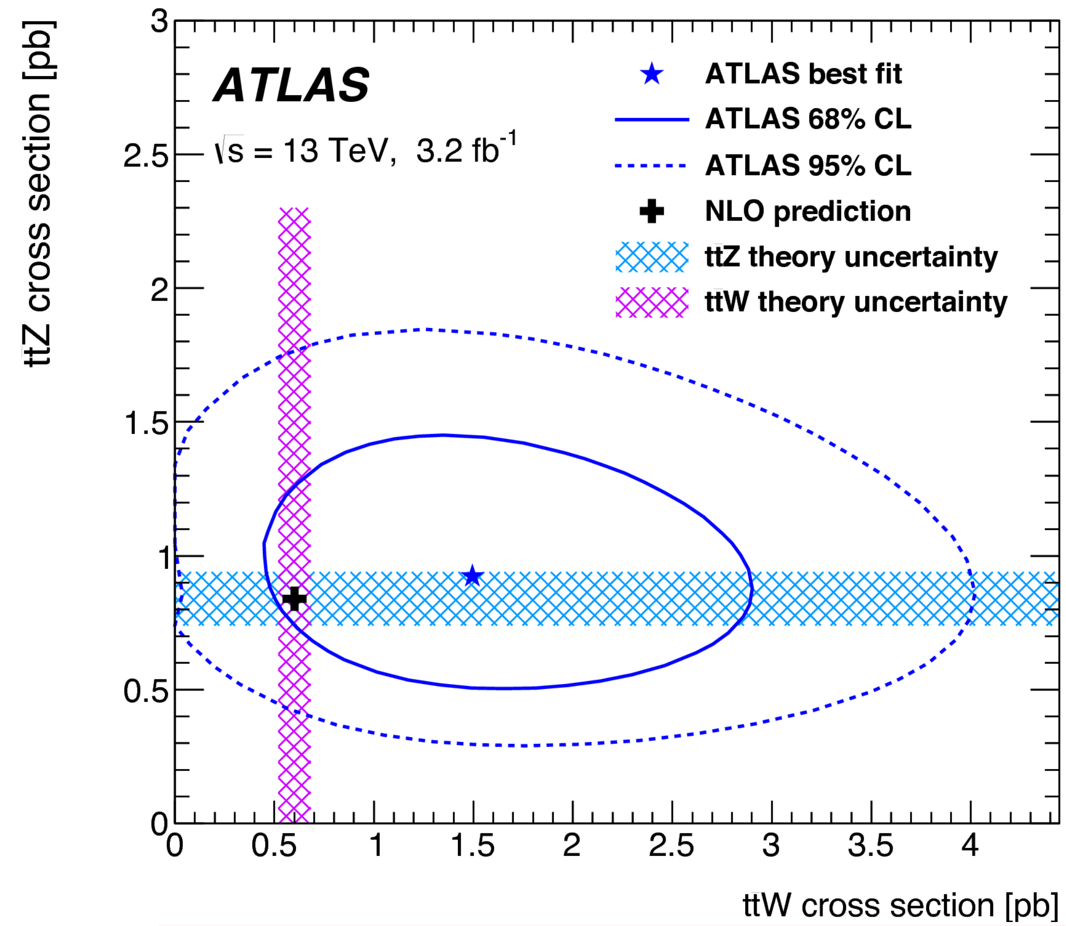




$t\bar{t}+W/Z$: Results

Simultaneous profile likelihood fit in 9 signal and 2 control regions





$\sigma(t\bar{t}Z) = 0.9 \pm 0.3$ pb (~33.3%)
$\sigma(t\bar{t}W) = 1.5 \pm 0.8$ pb (~53.3%)
correlation : -0.13

Dominated by statistical uncertainty (31% and 48%)

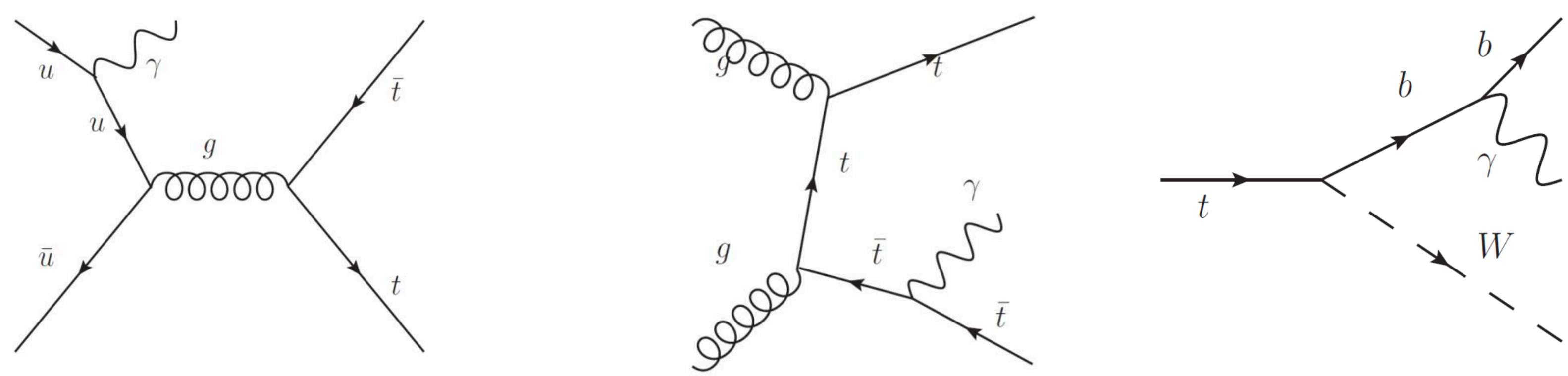
Observed (expected) significance over the background-only hypothesis:

- 3.9σ (3.4σ) for $t\bar{t}Z$
- 2.2σ (1.0σ) for $t\bar{t}W$

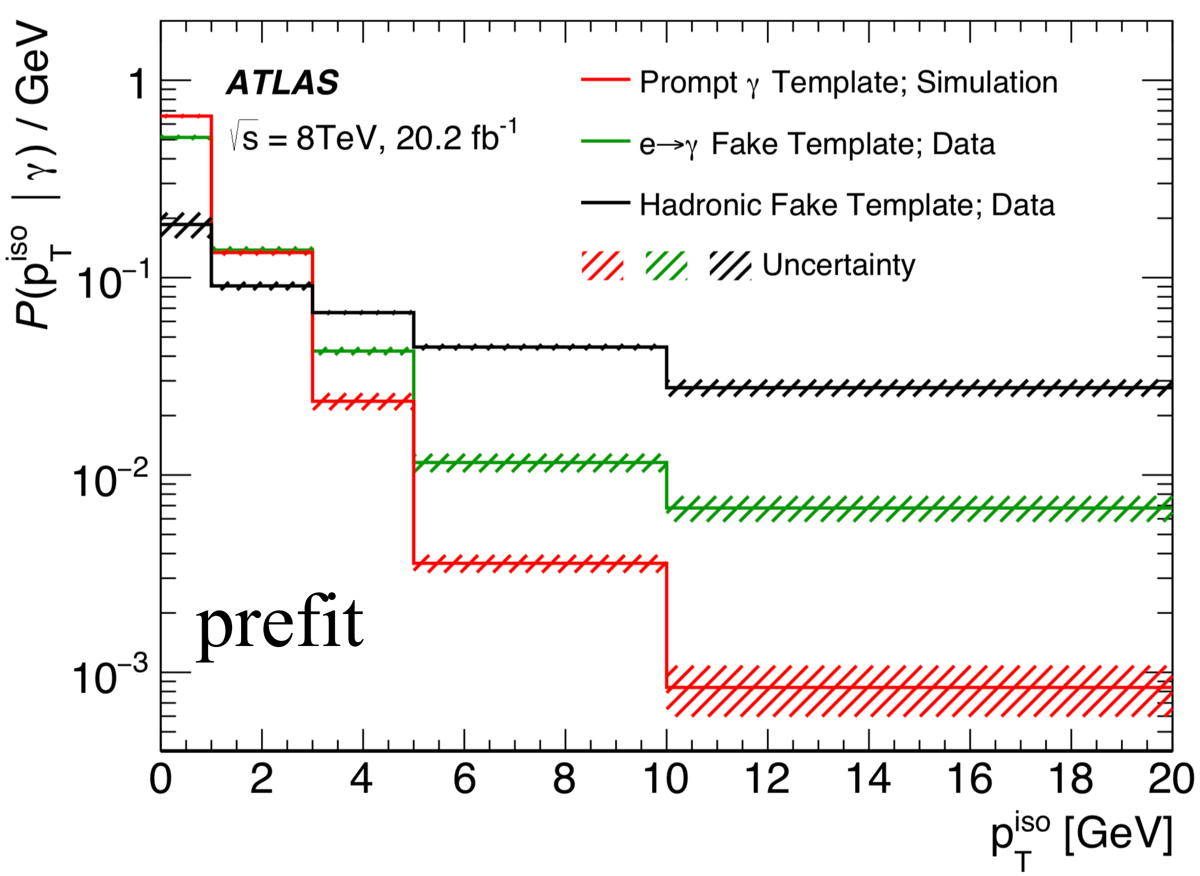
$t\bar{t}+\gamma$ @ 8TeV: 20.2 fb^{-1} JHEP 11 (2017) 086

- Direct probe of electroweak $t\gamma$ coupling
- Direct probe of V-A and A coupling at the $t\bar{t}\gamma$ vertex
- Dominant background in $t\bar{t}+H(\to\gamma\gamma)$

ISR | from top quark | FSR



Optimized selection to enhance photons from top quark and to suppress ISR/FSR



Measured in e/μ+*jets* final state state

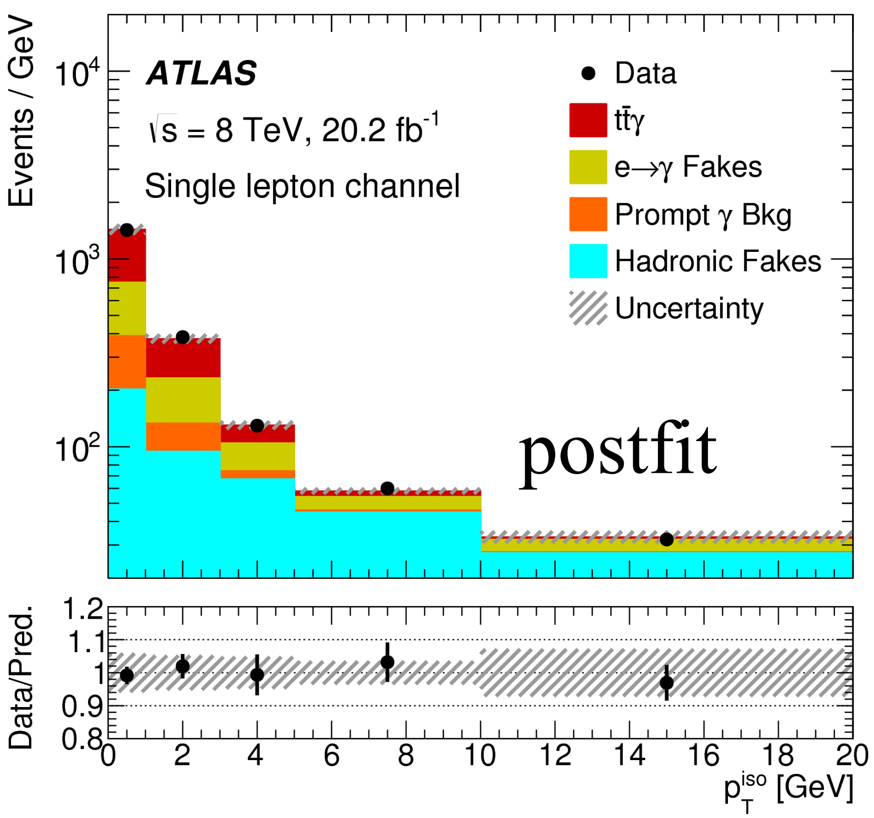
Background template for p_T^{iso} extracted from control regions

* p_T^{iso} = sum of the tracks within $\Delta R = 0.2$ around a photon

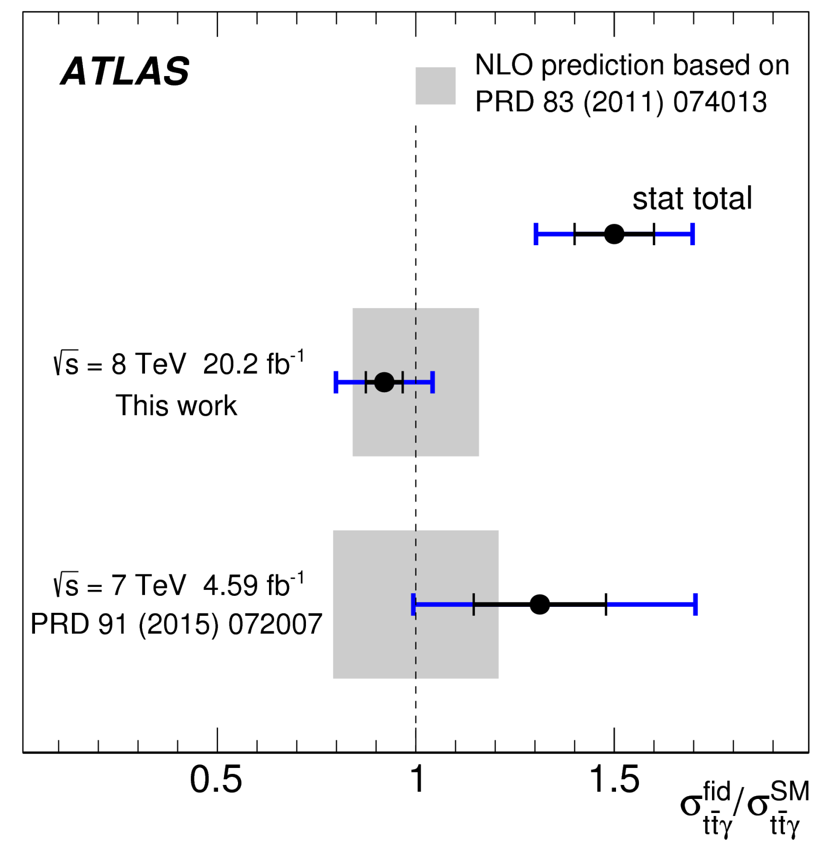
$t\bar{t}+\gamma$: inclusive cross section

Maximum likelihood fit of signal and background templates

Dominant uncertainties are hadron and electron fake estimate and statistics



Source	Relative uncertainty [%]
Hadron-fake template	6.3
$e \to \gamma$ fake	6.3
Jet energy scale	4.9
$W\gamma$+jets	4.0
$Z\gamma$+jets	2.8
Initial- and final-state radiation	2.2
Luminosity	2.1
Photon	1.4
Single top+γ	1.2
Muon	1.2
Electron	1.0
Scale uncertainty	0.6
Parton shower	0.6
Statistical uncertainty	5.1
Total uncertainty	13



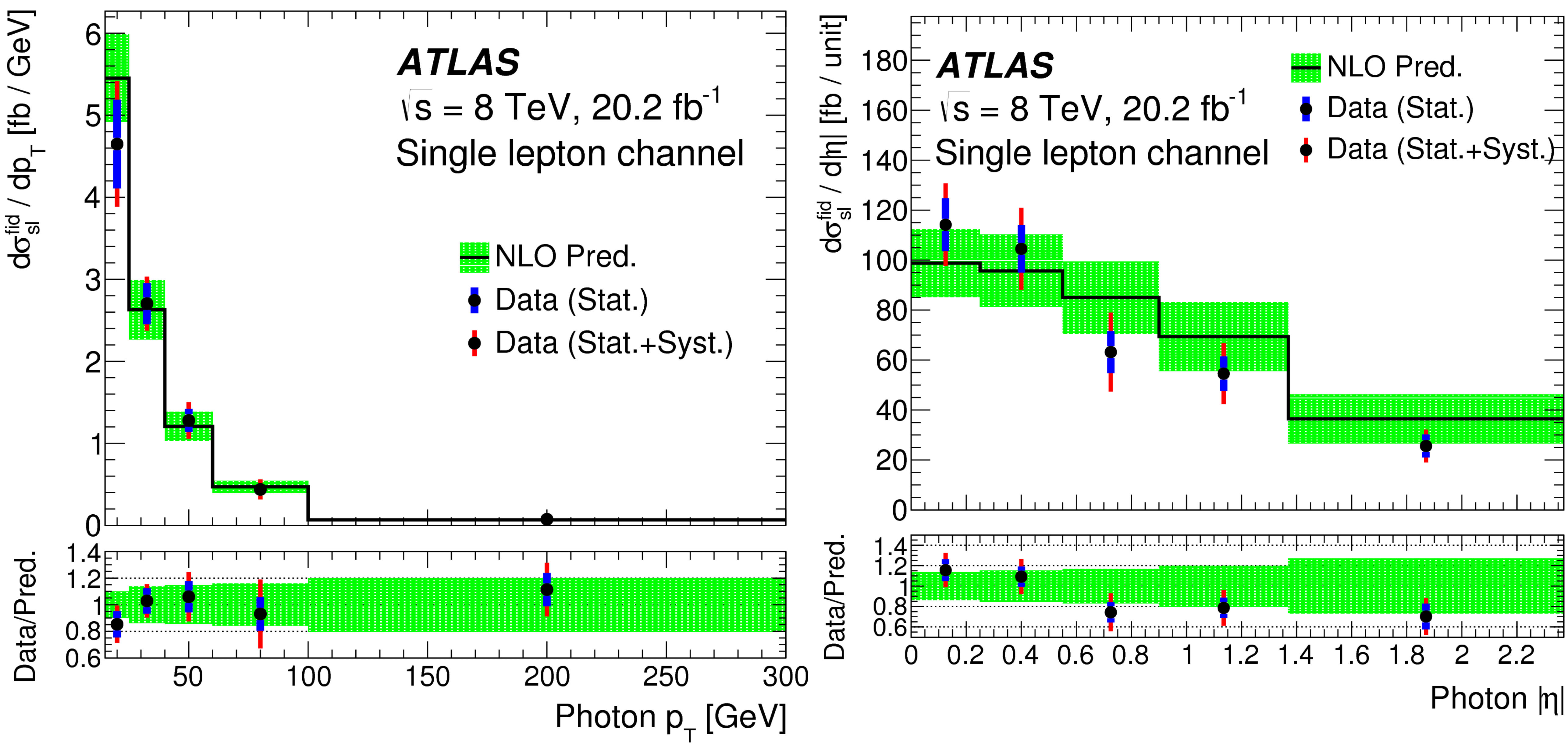
$\sigma_{fid} = 139 \pm 7$ (stat) $\pm$ 17 (syst.)fb. (~13%)

$\sigma_{theory} = 151 \pm 24$ fb (~16%)

$t\bar{t}+\gamma$: differential cross section

Photon p_T and $|\eta|$ distributions are unfolded to particle level

The calculated differential cross sections are in good agreement with theoretical predictions at NLO



Summary

- $t\bar{t}+X$ measurements is an active field of research at the LHC.
- The current status of the measurements at the ATLAS experiment for center of mass energy of 13 TeV (3.2 fb^{-1}) and 8 TeV has been presented.
- The measurements focused towards a less model dependent approach by using well defined fiducial volume and unfolding procedures.
- These measurements will provide strong constraints on the next iteration of Monte Carlo tuning.
- Precision measurements of $t\bar{t}+X$ will require larger statistics and can be achieved with the large integrated luminosity of Run II.

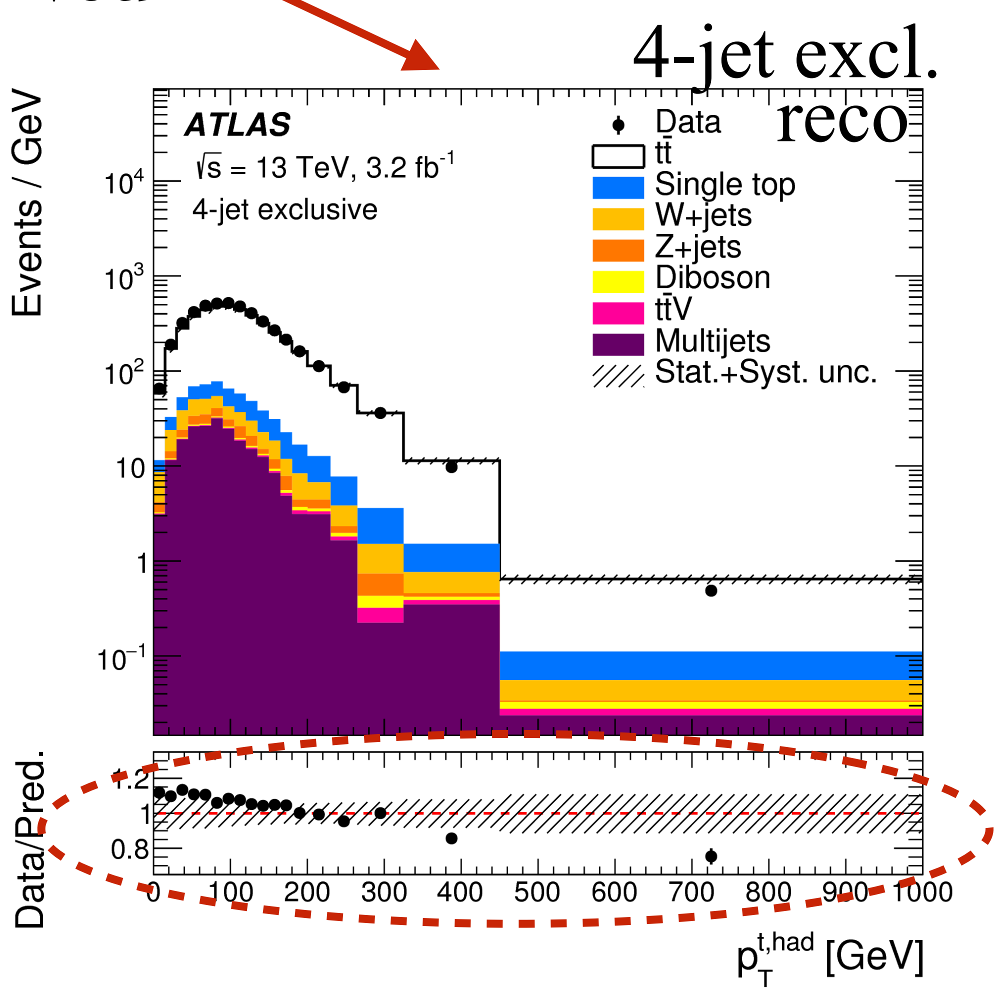
Thank you!

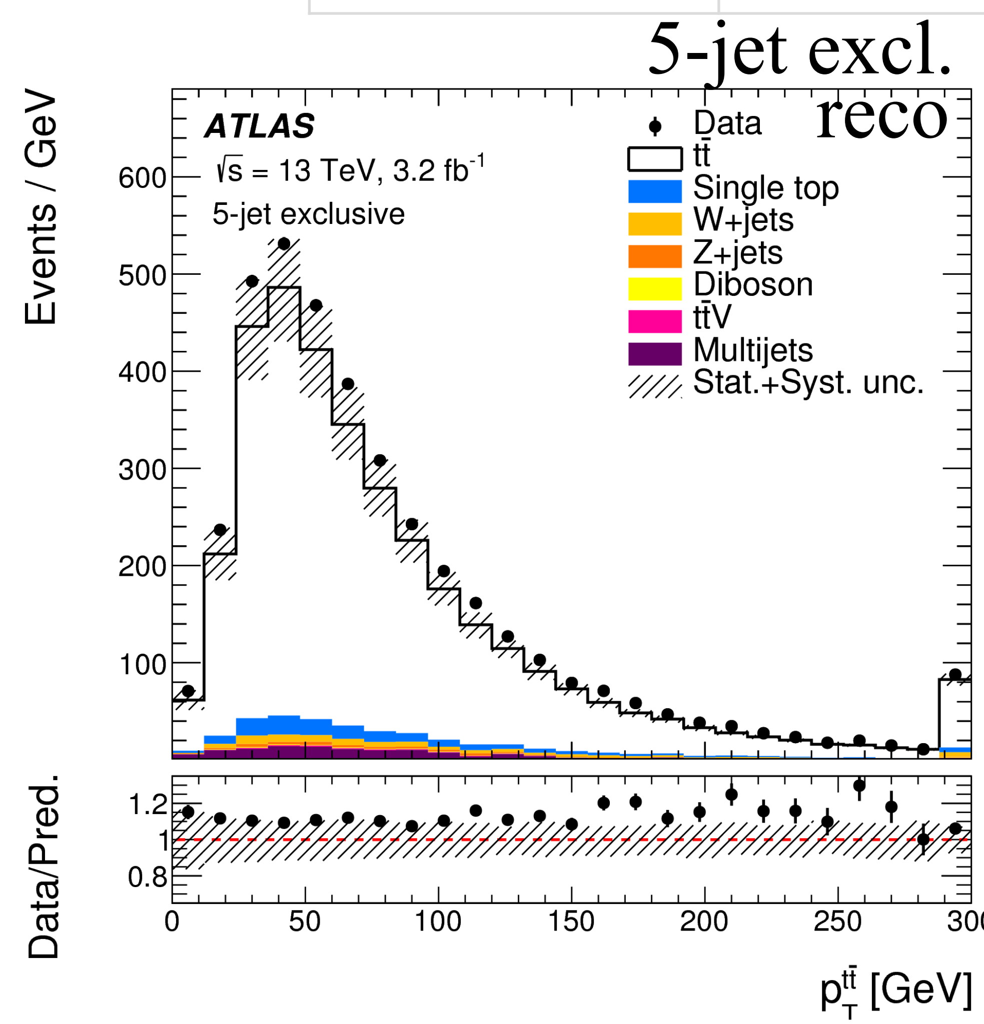
BONUS

$t\bar{t}$ + n-jets in e/μ events

- Probe the effect of gluon radiation on the kinematic variables of tt production
- 4-jet excl., 5-jet excl., 6-jet incl. regions
- Discrepancy in the pT(t-had) is observed

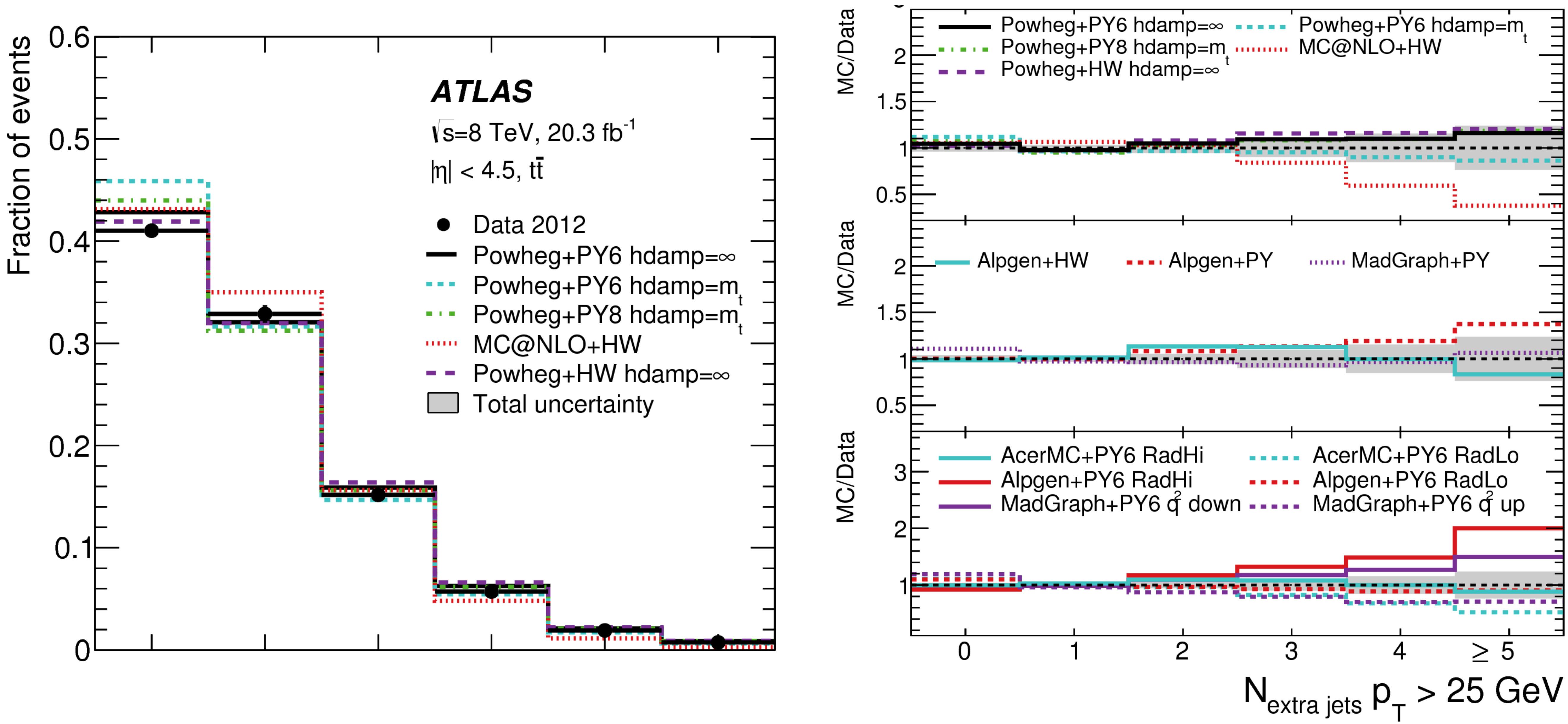
Background	Estimation
Single top ~ 5%	simulation and normalized to predicted cross section
Multijet ~ 4%	data driven
W+jets ~ 2 - 3%	shape in simulation, normalization of heavy flavor fraction from data
Z+jets, ttV, VV ~ 1- 2%	in simulation and normalized to predicted cross sections.





- The distributions are unfolded to particle level

eμ events: jet multiplicities- additional models



eμ events: χ^2 for additional jet pT spectra

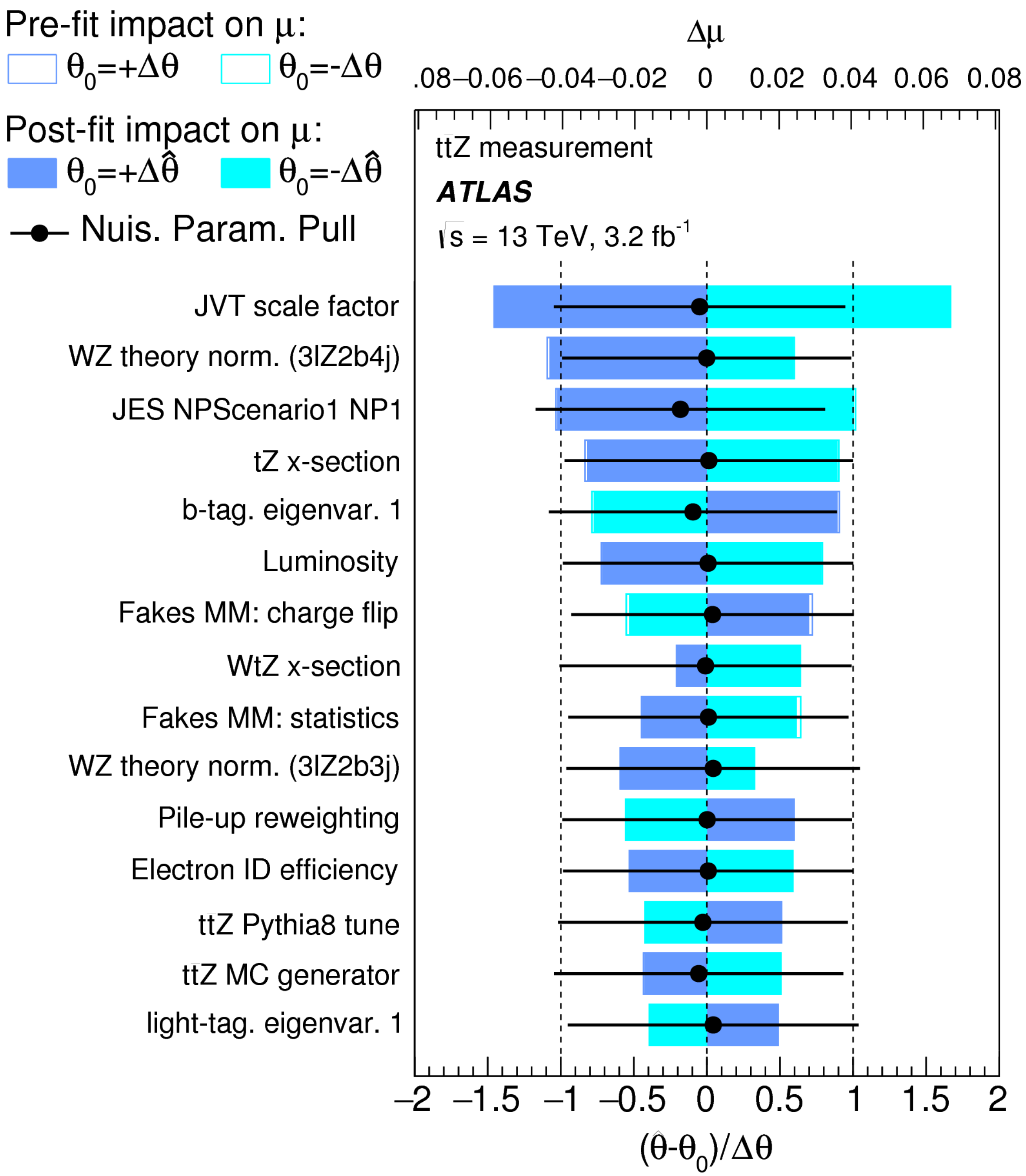
Generator	χ^2	p-value
POWHEG+PYTHIA6 $h_{\mathrm{damp}} = \infty$	55.3	6.7×10^{-2}
POWHEG+PYTHIA6 $h_{\mathrm{damp}} = m_t$	57.4	4.6×10^{-2}
POWHEG+PYTHIA8 $h_{\mathrm{damp}} = m_t$	78.0	4.4×10^{-4}
MC@NLO+HERWIG	108.2	5.8×10^{-8}
POWHEG+HERWIG $h_{\mathrm{damp}} = \infty$	51.4	1.3×10^{-1}
ALPGEN+HERWIG	64.0	1.2×10^{-2}
ALPGEN+PYTHIA6	55.5	6.4×10^{-2}
MADGRAPH+PYTHIA6	54.7	7.4×10^{-2}
ACERMC+PYTHIA6 RadHi	138.4	1.8×10^{-12}
ACERMC+PYTHIA6 RadLo	148.1	4.9×10^{-14}
ALPGEN+PYTHIA6 RadHi	104.7	1.8×10^{-7}
ALPGEN+PYTHIA6 RadLo	47.9	2.1×10^{-1}
MADGRAPH+PYTHIA6 q^2 down	50.2	1.5×10^{-1}
MADGRAPH+PYTHIA6 q^2 up	78.7	3.6×10^{-4}

e/μ events: χ^2

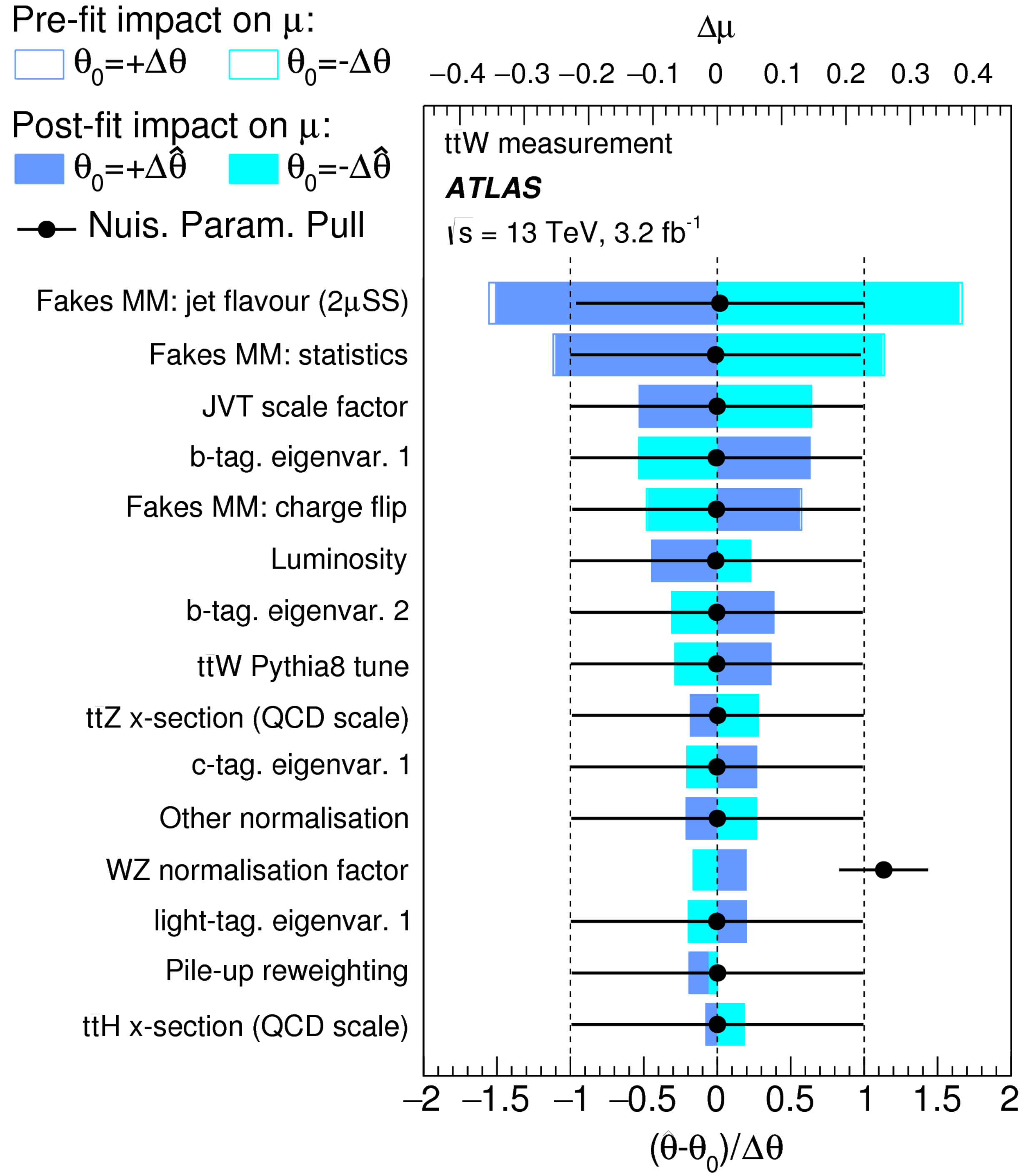
pT(t-had)	4-jet exclusive		5-jet exclusive		6-jet inclusive	
	χ^2/NDF	p-value	χ^2/NDF	p-value	χ^2/NDF	p-value
Powheg+Pythia6	28.9/18	0.05	13.0/18	0.79	13.0/18	0.79
Powheg+Pythia6 (radHi)	29.2/18	0.05	14.7/18	0.68	17.2/18	0.51
Powheg+Pythia6 (radLo)	32.5/18	0.02	14.3/18	0.71	13.9/18	0.74
Powheg+Pythia8 ($h_{\mathrm{damp}} = m_t$)	25.2/18	0.12	14.7/18	0.68	15.7/18	0.61
Powheg+Pythia8 ($h_{\mathrm{damp}} = 1.5\,m_t$)	22.7/18	0.20	13.3/18	0.77	16.3/18	0.57
Powheg+Pythia8 (radHi) ($h_{\mathrm{damp}} = 3\,m_t$)	20.0/18	0.33	14.5/18	0.70	23.9/18	0.16
Powheg+Pythia8 (radLo) ($h_{\mathrm{damp}} = 1.5\,m_t$)	24.7/18	0.13	14.7/18	0.68	13.1/18	0.79
Powheg+Herwig7	20.8/18	0.29	12.0/18	0.85	12.4/18	0.82
Powheg+Herwig++	37.1/18	¡0.01	27.7/18	0.07	38.7/18	¡0.01
MadGraph5_aMC@NLO+Herwig++	25.7/18	0.11	11.1/18	0.89	20.3/18	0.32
MadGraph5_aMC@NLO+Pythia8 ($H_{\mathrm{T}}/2$)	22.9/18	0.19	21.2/18	0.27	17.7/18	0.47
MadGraph5_aMC@NLO+Pythia8 ($\sqrt{m_t^2 + p_{\mathrm{T}}^2}$)	25.4/18	0.11	19.3/18	0.37	23.1/18	0.18
Sherpa 2.2.1	24.7/18	0.14	18.3/18	0.43	18.3/18	0.44

pT(tt)	4-jet exclusive		5-jet exclusive		6-jet inclusive	
	χ^2/NDF	p-value	χ^2/NDF	p-value	χ^2/NDF	p-value
Powheg+Pythia6	7.9/6	0.25	6.0/6	0.43	6.4/6	0.38
Powheg+Pythia6 (radHi)	15.9/6	0.01	5.8/6	0.45	36.2/6	¡0.01
Powheg+Pythia6 (radLo)	4.9/6	0.56	5.8/6	0.45	6.5/6	0.37
Powheg+Pythia8 ($h_{\mathrm{damp}} = m_t$)	7.3/6	0.29	5.7/6	0.45	8.0/6	0.24
Powheg+Pythia8 ($h_{\mathrm{damp}} = 1.5\,m_t$)	7.6/6	0.27	3.3/6	0.77	12.3/6	0.06
Powheg+Pythia8 (radHi) ($h_{\mathrm{damp}} = 3\,m_t$)	13.9/6	0.03	3.2/6	0.78	54.8/6	¡0.01
Powheg+Pythia8 (radLo) ($h_{\mathrm{damp}} = 1.5\,m_t$)	5.5/6	0.49	5.0/6	0.55	6.6/6	0.36
Powheg+Herwig7	10.2/6	0.12	5.1/6	0.53	5.0/6	0.54
Powheg+Herwig++	8.2/6	0.23	25.8/6	¡0.01	20.8/6	¡0.01
MadGraph5_aMC@NLO+Herwig++	98.3/6	¡0.01	8.6/6	0.20	12.4/6	0.05
MadGraph5_aMC@NLO+Pythia8 ($H_{\mathrm{T}}/2$)	41.2/6	¡0.01	34.5/6	¡0.01	22.8/6	¡0.01
MadGraph5_aMC@NLO+Pythia8 ($\sqrt{m_t^2 + p_{\mathrm{T}}^2}$)	46.7/6	¡0.01	31.4/6	¡0.01	18.6/6	¡0.01
Sherpa 2.2.1	13.3/6	0.04	1.8/6	0.94	21.7/6	¡0.01

tt+V: fit



Pre-fit impact on μ:
θ0=+Δθ θ0=-Δθ
Post-fit impact on μ:
θ0=+Δθ̂ θ0=-Δθ̂
Nuis. Param. Pull
Δμ
ttZ measurement
ATLAS
√s = 13 TeV, 3.2 fb-1
JVT scale factor
WZ theory norm. (3lZ2b4j)
JES NPScenario1 NP1
tZ x-section
b-tag. eigenvar. 1
Luminosity
Fakes MM: charge flip
WtZ x-section
Fakes MM: statistics
WZ theory norm. (3lZ2b3j)
Pile-up reweighting
Electron ID efficiency
ttZ Pythia8 tune
ttZ MC generator
light-tag. eigenvar. 1
(θ-θ0)/Δθ



Pre-fit impact on μ:
θ0=+Δθ θ0=-Δθ
Post-fit impact on μ:
θ0=+Δθ̂ θ0=-Δθ̂
Nuis. Param. Pull
Δμ
ttW measurement
ATLAS
√s = 13 TeV, 3.2 fb-1
Fakes MM: jet flavour (2μSS)
Fakes MM: statistics
JVT scale factor
b-tag. eigenvar. 1
Fakes MM: charge flip
Luminosity
b-tag. eigenvar. 2
ttW Pythia8 tune
ttZ x-section (QCD scale)
c-tag. eigenvar. 1
Other normalisation
WZ normalisation factor
light-tag. eigenvar. 1
Pile-up reweighting
ttH x-section (QCD scale)
(θ-θ0)/Δθ

$t\bar{t}+W/Z$: uncertainties and fit

Dominated by statistical uncertainty

Reconstructed objects is the main source of systematic uncertainties

Simultaneous profile likelihood fit in 9 signal and 2 control regions

WZ and *ZZ* normalizations are free parameters of the fit

Uncertainty	$\sigma_{t\bar{t}Z}$	$\sigma_{t\bar{t}W}$
Luminosity	2.6%	3.1%
Reconstructed objects	8.3%	9.3%
Backgrounds from simulation	5.3%	3.1%
Fake leptons and charge misID	3.0%	19%
Signal modelling	2.3%	4.2%
Total systematic	11%	22%
Statistical	31%	48%
Total	32%	53%