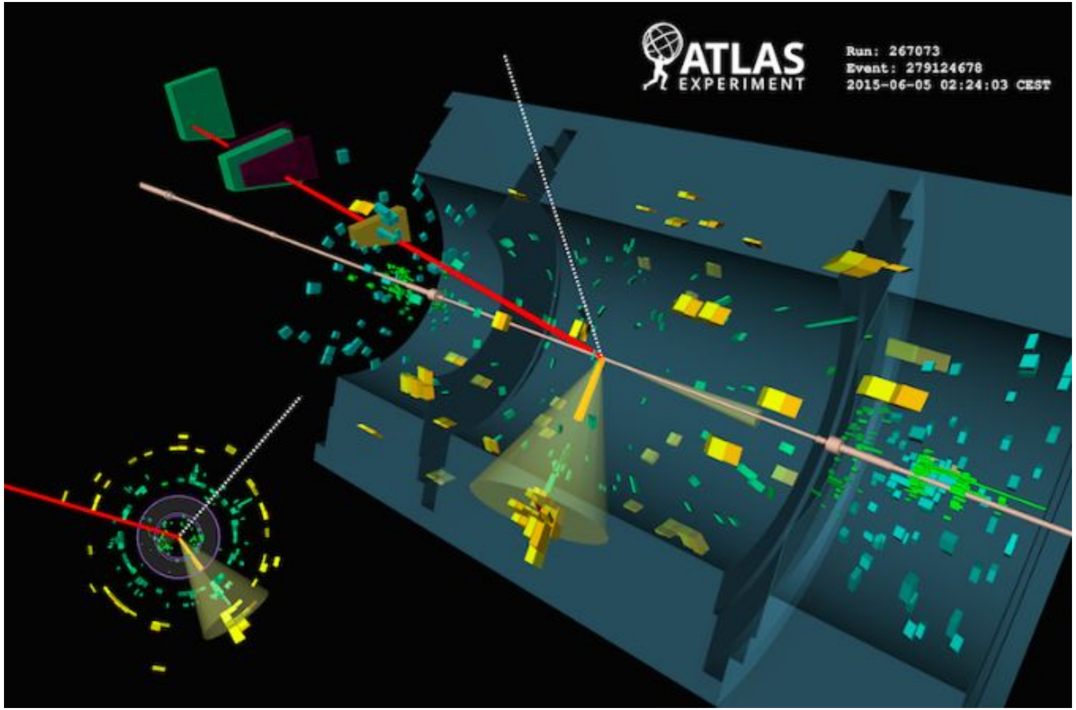
Measurements of tV and ttV production with ATLAS and CMS detectors



Alvaro Lopez Solis

On behalf of ATLAS and CMS collaborations

CKM Workshop 2021
University of Melbourne
24th November 2021

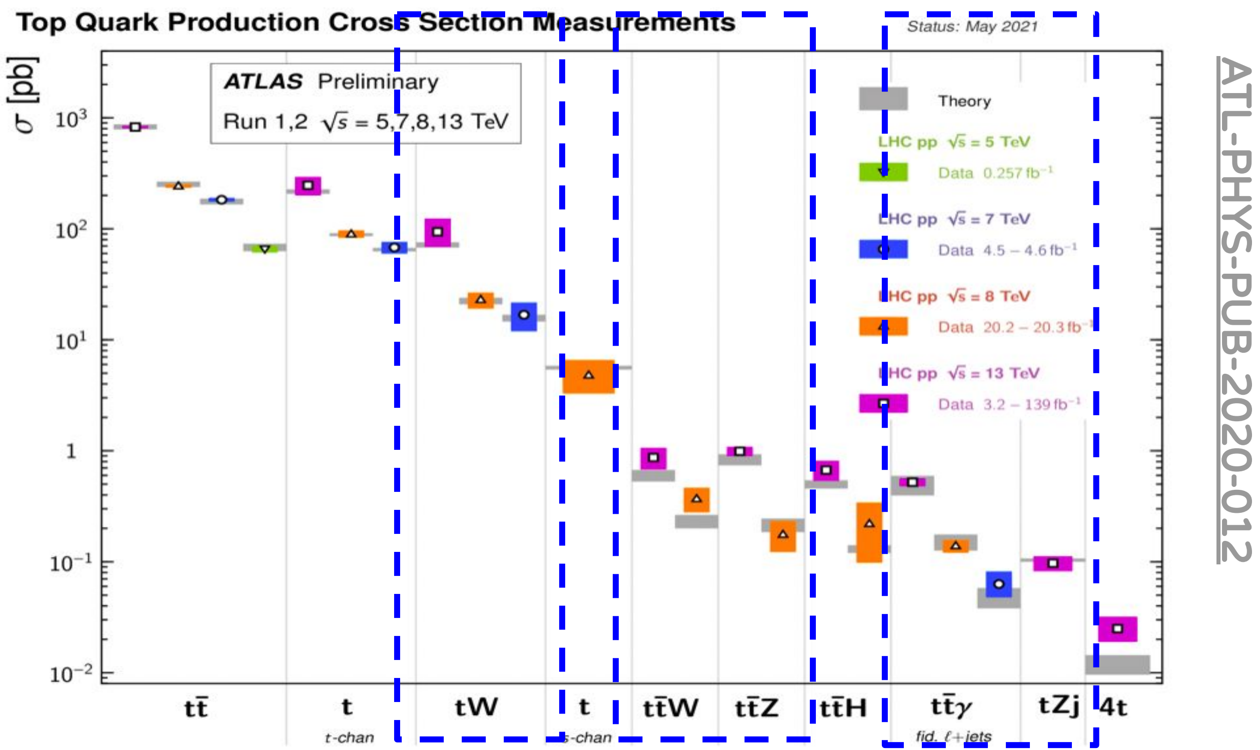
ATLAS EXPERIMENT

CMS

DESY.

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Overview

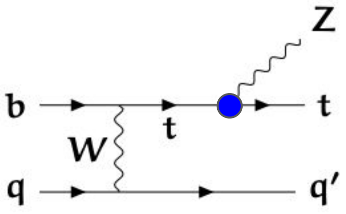


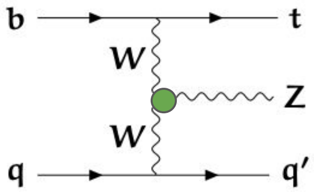
Top properties and production cross-section measurements are key in LHC physics program

Motivation of t(t)V measurements

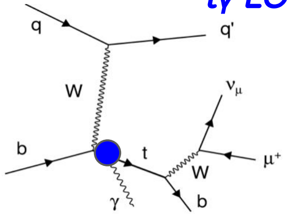
- ttV and tV processes are probes of electroweak couplings of the top to weak bosons
  - Sensitive to anomalous couplings in the EWK sector.
  - Sensitive to CP violation couplings, Vtb measurements.
- ttZ/ ttW: irreducible background in several key LHC searches
- tZq: purely produced by top-EWK couplings
  - strongly polarised top -> probe of t/t spin asymmetry.
  - In addition, probe to triple WWZ coupling.
- tγ and ttγ: probe of top-quark/γ couplings
- Differential measurements to help in MC tuning and anomalous couplings.

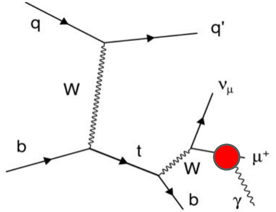
tZq LO



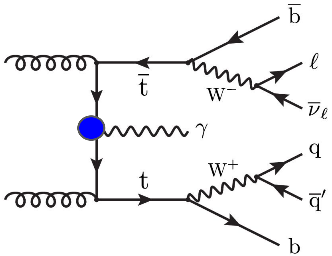


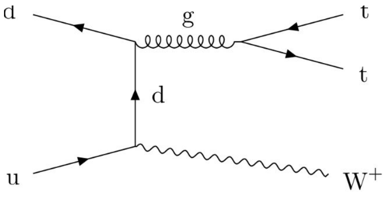
tγ LO

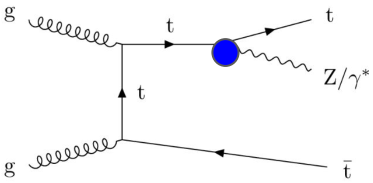




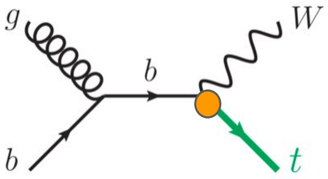
ttγ, ttW and ttZ LO diagrams







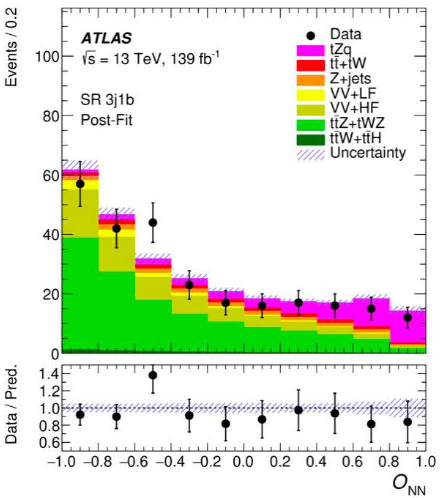
Single-top tW LO

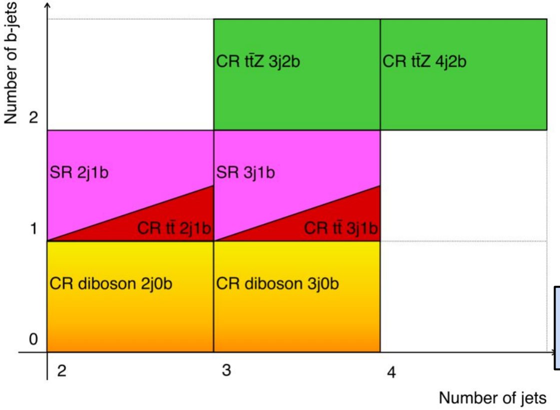


See Alejandro Soto's talk

σ^{tZq} incl. measurements

- Searching in 3 lepton regions. 1 b-jet and 1 or 2 additional non b-tagged jets
  - Signal includes resonant Z-boson and non-resonant diagrams ($m_{\ell\ell} > 30$ GeV)
  - Z/top mass reco.: lepton pair assigned to Z if $|m_{\ell\ell}-m_Z| < 10$ GeV, other to top (ℓ_t)
- Dominated by VV and ttZ (prompt lepton) and Z+jets and *tt* (non-prompt lepton)
  - Dedicated CRs in 3ℓ (prompt-lepton) and $2\ell + 2b$ (non-prompt)
- NN to increase sensitivity to tZq
  - Based on leptons from Z, jets, top, b-tagging information
- Inclusive cross-section extracted from template fit in NN score (tZq, ttZ), m_T (VV), yield (ttbar)
  - Dominated by prompt lepton modelling and jet/lepton uncertainties





$\sigma^{tZq}_{ATLAS} = 97^{+13}_{-13}(\text{stat})^{+7}_{-7}(\text{syst})$ fb (14% precision)

For $m_{\ell\ell}$ > 30 GeV

$\sigma^{NLO}_{SM} = 102^{+5.2}_{-1.3}$ (scale) $^{+1.0}_{-1.0}$(PDF) fb

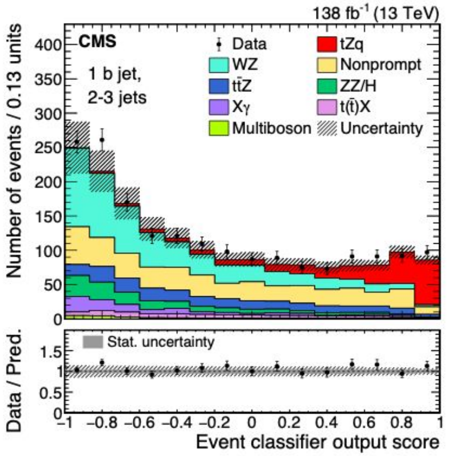
Uncertainty source	$\Delta\sigma/\sigma$ [%]
Prompt-lepton background modelling and normalisation	3.3
Jets and E_T^{miss} reconstruction and calibration	2.0
Lepton reconstruction and calibration	2.0
Luminosity	1.7
Non-prompt-lepton background modelling	1.6
Pile-up modelling	1.2
MC statistics	1.0
tZq modelling (QCD radiation)	0.8
tZq modelling (PDF)	0.7
Jet flavour tagging	0.4
Total systematic uncertainty	7.0
Data statistics	12.6
$t\bar{t} + tW$ and $Z+$jets normalisation	2.1
Total statistical uncertainty	12.9

arXiv:2111.02860

NEW

σ^{tZq} incl. and diff. measurements

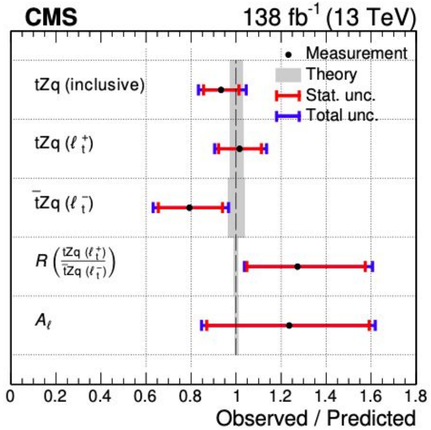
- Searching in 3 lepton regions (Z->ℓℓ and t->ℓvb)
  - 1 b-jet, at least 1 additional jet (high-p_T, forward)
  - 3 leptons: pair assigned to Z within $|m_{ll}-m_Z| < 15$ GeV , other to top (ℓ_t)
- Dominated by ttZ, WZ, Zγ and non-prompt
- Non-prompt lepton background limited previous results.
  - Mainly coming from *tt* and Z+jets background
  - Dedicated BDT lepton identification (lepton MVA)
- BDT to separate signal from bkg. Based on lepton, jets, top, b-tagging information
- Inclusive cross-section extracted from MLE fit on BDT output score
  - Three SRs: N_b=1, N_j=2 or 3 (WZ); N_b=1, N_j>=4 (ttZ (4ℓ), WZ); N_b=2, N_j>=4 (ttZ)
  - Dominated by tZq μ_R/μ_F , bkgs normalizations, b-tagging uncertainties.
- ℓ_t charge to separate SRs to evaluate $\sigma^{tZq}(\ell+)/\sigma^{tZq}(\ell-)$



$\sigma^{tZq}_{CMS} = 87.9^{+7.5}_{-7.3}(\text{stat})^{+7.3}_{-6.0}(\text{syst})$ fb
(11% precision)

For $m_{\ell\ell}$> 30 GeV

$\sigma^{th}_{NLO}(5FS) = 94.2^{+1.9}_{-1.8}(\text{scale})^{+2.5}_{-2.5}(\text{PDF})$ fb

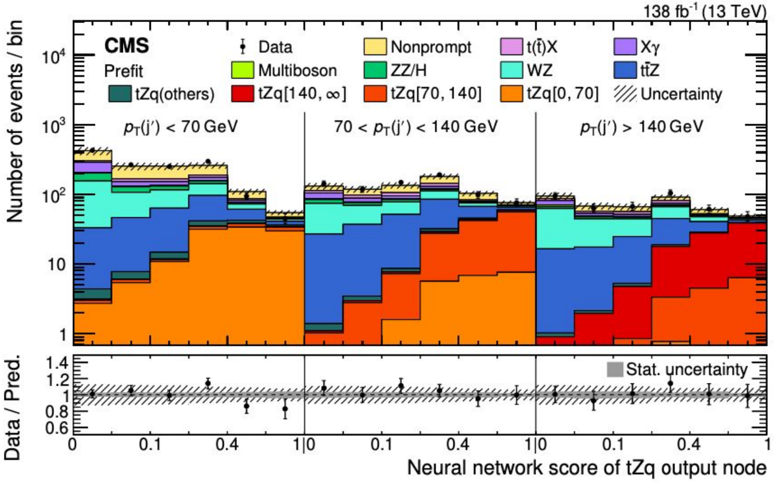


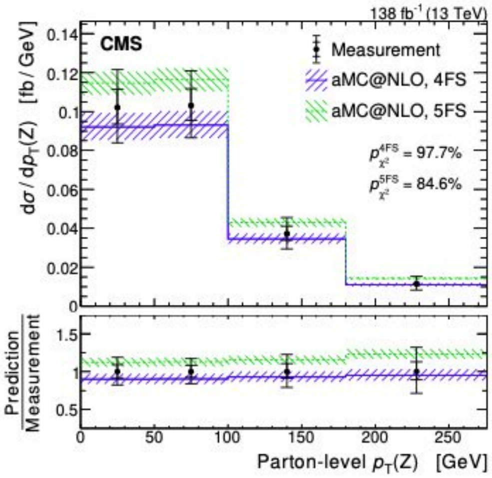
NEW

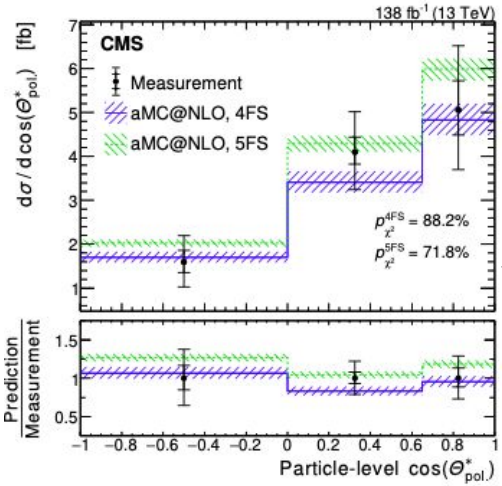
arXiv:2111.02860

σ^{tZq} incl. and diff. measurements

- Differential cross-section measurement with re-optimized selection
  - Neural network to extract tZq signal
- Template fit: observable of diff. cross-section + NN score.
- Unfolding through likelihood-based technique:
  - $p_T(Z)$, $m_{\ell\ell\ell}$, $p_T(\ell_t)$, $\cos(\theta^*)$, $\Delta\varphi(\ell,\ell)$, $m(tZ)$, $p_T(j')$, $|\eta(j')|$
- Good agreement with MG5_atNLO except for $m_{\ell\ell\ell}$
  - 5FS vs 4FS: mainly normalization differences.
  - Sensitivity not enough to show a preference
- Spin asymmetry fitted from parton-level cosθ*







$$\cos(\theta^\star_{\mathrm{pol}}) = \frac{\vec{p}(q'^\star)\cdot\vec{p}(\ell^\star_t)}{|\vec{p}(q'^\star)||\vec{p}(\ell^\star_t)|}, \qquad \frac{d\sigma}{d\cos(\theta^\star_{\mathrm{pol}})} = \sigma_{tZq}\left(\frac{1}{2} + A_\ell \cos(\theta^\star_{\mathrm{pol}})\right).$$

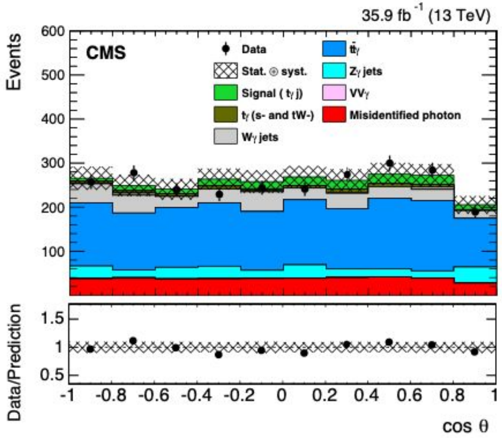
$A^l_{CMS}(tZq) = 0.54^{+0.16}_{-0.16}(stat)^{+0.06}_{-0.06}(syst)$

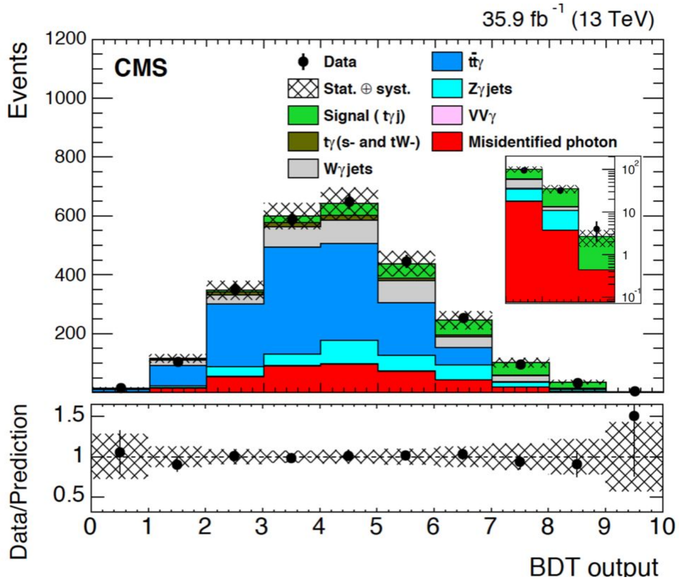
$A^{l,4FS}_{MG5@NLO}(tZq) = 0.44$; $A^{l,5FS}_{MG5@NLO}(tZq) = 0.45$

$\sigma^{t\gamma}$ inclusive measurement

- Measured in 35.9 fb^{-1}. Focusing on 1μ decay channel (*t*->μνb)
- Selection based on presence of 1γ, 1μ, 1 b-jet and 1 forward jet.
- Dominant background is ttγ. Backgrounds are divided in
  - Genuine-γ (ttγ, Vγ, VVγ, ..): from MC. ttγ CR defined.
  - Non-prompt photon: p_T-dependent prob of misidentification of j/e->γ from data-driven technique.
- BDT to increase signal discrimination
  - Based on object kinematics and reconstructed top mass.
- Cross-section from simultaneous fit of BDT shape in SR and ttγ CR
  - Dominant uncertainties from jet calibration, signal modelling, Zγ normalization and b-tagging

Process	Event yield
$t\bar{t}+\gamma$	1401 ± 131
$W\gamma$+jets	329 ± 78
$Z\gamma$+jets	232 ± 55
Misidentified photon	374 ± 74
$t\gamma$ (*s*- and tW-channel)	57 ± 8
$VV\gamma$	8 ± 3
Total background	2401 ± 178
Expected signal	154 ± 24
Total SM prediction	2555 ± 180
Data	2535





$\sigma_{CMS}(t\gamma) = 115^{+17}_{-17}(\text{stat})^{+30}_{-30}(\text{syst})$ fb

Significance = 4.4 σ (exp 3.0 σ)

$\sigma_{theo}(t\gamma) = 81^{+4}_{-4}$ pb

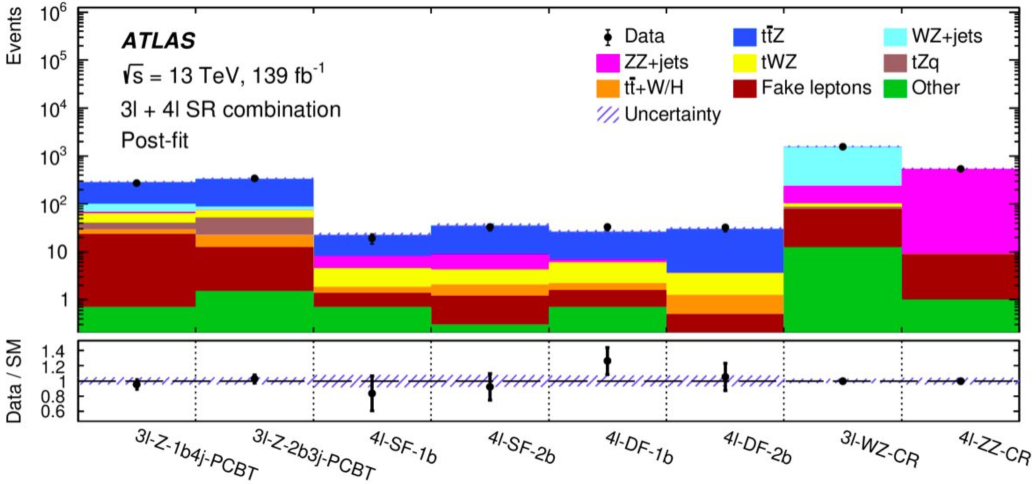
https://doi.org/10.1103/PhysRevD.88.033003

Eur. Phys. J. C 81 (2021) 737

σ^{ttZ} incl. and diff. measurements

- 3 lepton and 4 lepton signal regions with a Z-candidate ($|m_{\ell\ell} - m_Z| < 10$ GeV)
  - Binned in b-jet and lepton-flavour.
- Diboson dominating background in 3ℓ (WZ) and 4ℓ (ZZ) -> dedicated CRs
  - Fake lepton background obtained in data (mainly from dileptonic tt + HF)
    - Fake factors from data validated in dedicated VRs.
  - Other backgrounds from MC predictions.
- Results obtained by simultaneous fit of the $3\ell + 4\ell$ single-bin SRs and CRs
  - Dominated by modelling uncertainties (signal and background) and b-tagging

Uncertainty	$\Delta\sigma_{t\bar{t}Z}/\sigma_{t\bar{t}Z}$ [%]
$t\bar{t}Z$ parton shower	3.1
tWZ modelling	2.9
b-tagging	2.9
WZ/ZZ + jets modelling	2.8
tZq modelling	2.6
Lepton	2.3
Luminosity	2.2
Jets + E_T^{miss}	2.1
Fake leptons	2.1
$t\bar{t}Z$ ISR	1.6
$t\bar{t}Z$ μ_f and μ_r scales	0.9
Other backgrounds	0.7
Pile-up	0.7
$t\bar{t}Z$ PDF	0.2
Total systematic	8.4
Data statistics	5.2
Total	10



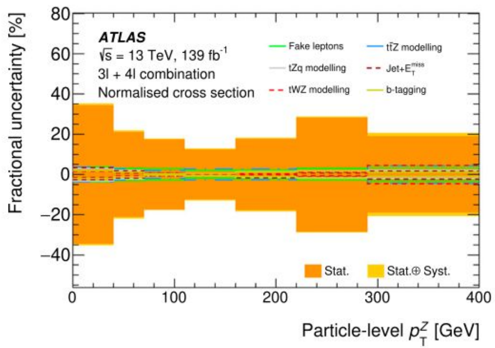
$\sigma_{ATLAS}(ttZ) = 0.99^{+0.05}_{-0.05}(stat)^{+0.08}_{-0.08}(syst)$ pb

$\sigma^{NLO+NNLL+EWK}_{theo}(ttZ) = 0.86^{+0.09}_{-0.10}$ pb

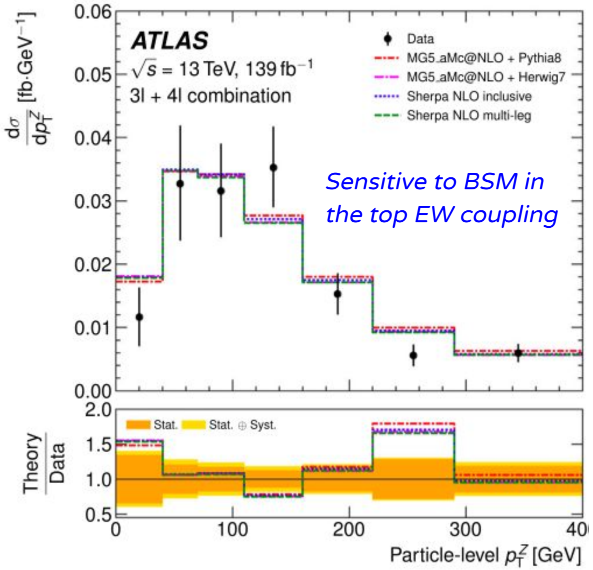
arxiv:1812.08622 arxiv:1907.04343

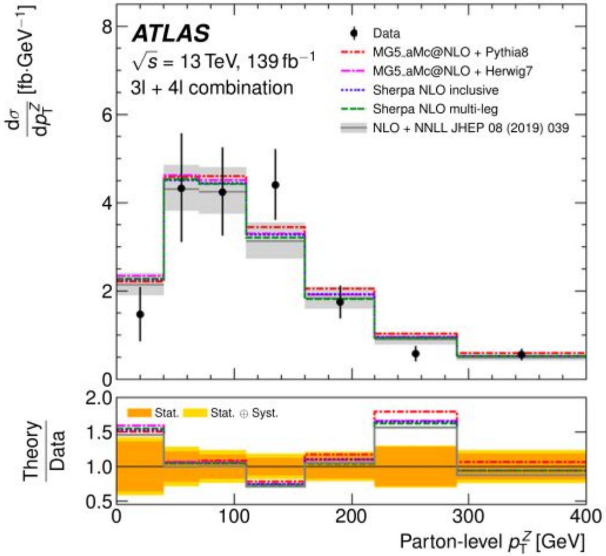
Eur. Phys. J. C 81 (2021) 737

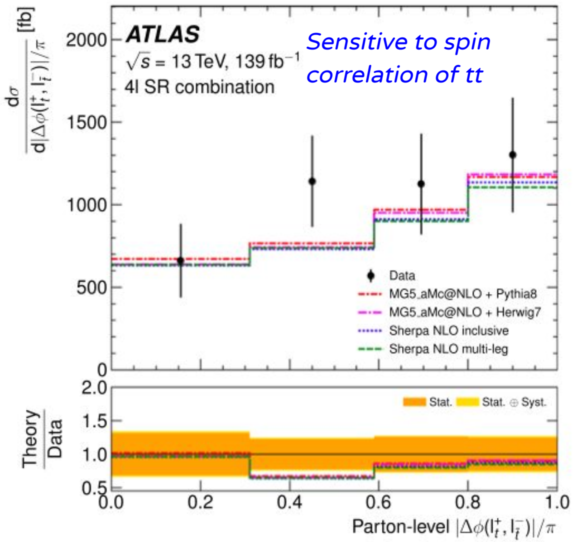
σ^{ttZ} incl. and diff. measurements



- Differential cross-section measurement into parton and particle level
  - Iterative Bayesian unfolding (RooUnfold) for $p_T(Z)$, $p_T(\ell$, non-$Z)$, $|\Delta\varphi(t_{lep},Z)|$, $|\Delta\varphi(tt,Z)|$
  - Except N_j (only particle-level)
- Some disagreements in $p_T(Z)$, although overall compatibility between predictions and data.
  - MG5@NLO and Sherpa comparisons.
  - Theory predictions to NLO+NNLL



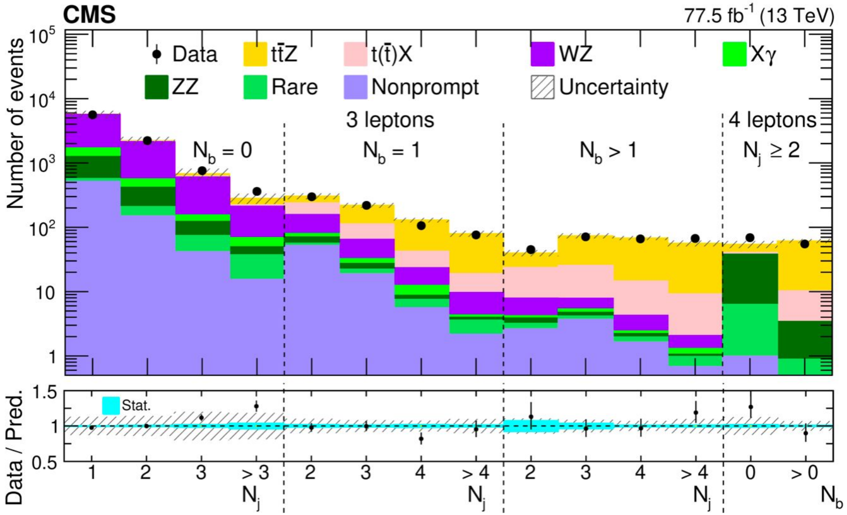




σ^{ttZ} incl. and diff. measurements

*t(t)X = tWZ, tZq, tHq, tttt, ttVV, tHW,ttW, ttH

- 3 lepton and 4 lepton signal regions.
  - 3 lepton binned in N_b and N_j -> Dominated by WZ and t(t)X*
    - Control regions of backgrounds in 3ℓ, $N_b = 0$
  - 4 lepton binned in N_b (required one Z-candidate) -> Dominated by ZZ
    - Control regions of backgrounds in 4ℓ + two Z-candidates
- Results obtained by simultaneous fit of the defined signal regions
  - Dominated by lepton identification uncertainties, the WZ cross-sectic and statistical uncertainties.



Source	Uncertainty range (%)	Correlated between 2016 and 2017	Impact on the $t\bar{t}Z$ cross section (%)
Integrated luminosity	2.5	×	2
PU modeling	1–2	✓	1
Trigger	2	×	2
Lepton ID efficiency	4.5–6	✓	4
Jet energy scale	1–9	✓	2
Jet energy resolution	0–1	✓	<1
b tagging light flavor	0–4	×	<1
b tagging heavy flavor	1–4	×	2
Choice in μ_R and μ_F	1–4	✓	1
PDF choice	1–2	✓	<1
Color reconnection	1.5	✓	1
Parton shower	1–8	✓	<1
WZ cross section	10	✓	3
WZ high jet multiplicity	20	✓	1
WZ + heavy flavor	8	✓	1
ZZ cross section	10	✓	1
$t(\bar{t})X$ background	10–15	✓	2
$X\gamma$ background	20	✓	1
Nonprompt background	30	✓	1
Rare SM background	50	✓	1
Stat. unc. in nonprompt bkg.	5–50	×	<1
Stat. unc. in rare SM bkg.	5–100	×	<1
Total systematic uncertainty			6
Statistical uncertainty			5
Total			8

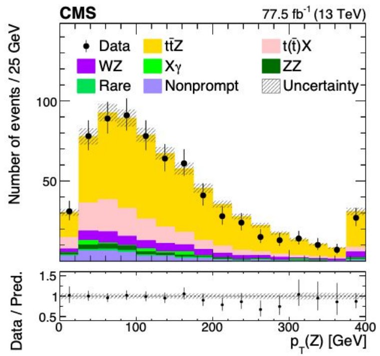
$\sigma_{CMS}(ttZ) = 0.95^{+0.05}_{-0.05}(stat)^{+0.06}_{-0.06}(syst)$ pb

$\sigma^{NLO+NNLL+EWK}_{theo}(ttZ) = 0.86^{+0.08}_{-0.09}(scale)^{+0.03}_{-0.03}(PDF)$ pb

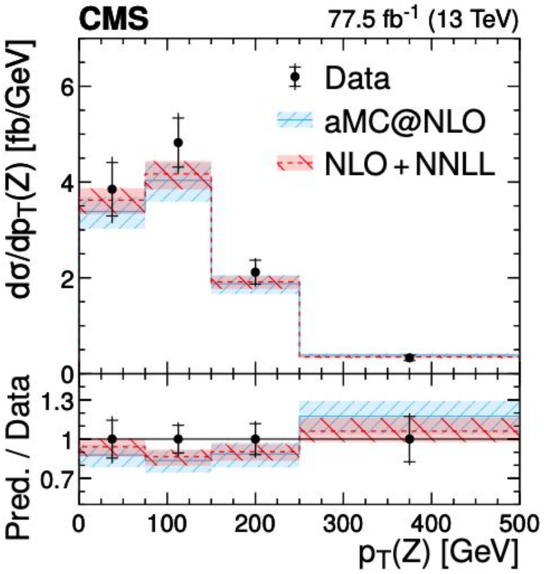
arxiv:1812.08622 arxiv:1907.04343

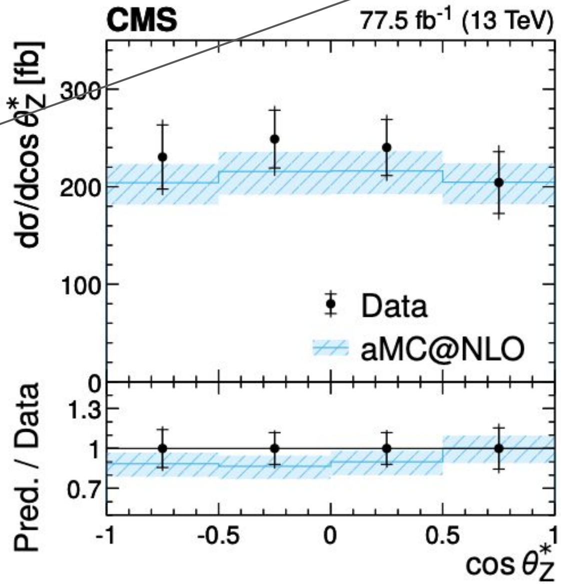
JHEP 03 (2020) 056

σ^{ttZ} incl. and diff. measurements

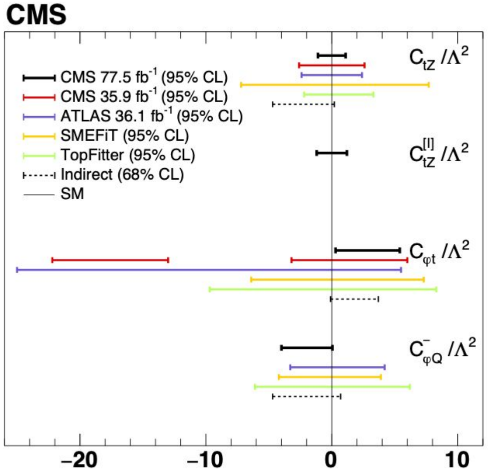


- Differential cross-section measurement with high-purity regions:
  - 3ℓ, 1 b-jet, 3 jets but limited by statistics -> Coarse binning of variables.
- Iterative Bayesian unfolding to $p_T(Z)$ and cosθ.
  - Sensitive to anomalous t-Z coupling
- Good agreement with MG5@NLO and NLO+NNLL predictions
- Evaluated anomalous couplings in the SMEFT framework.



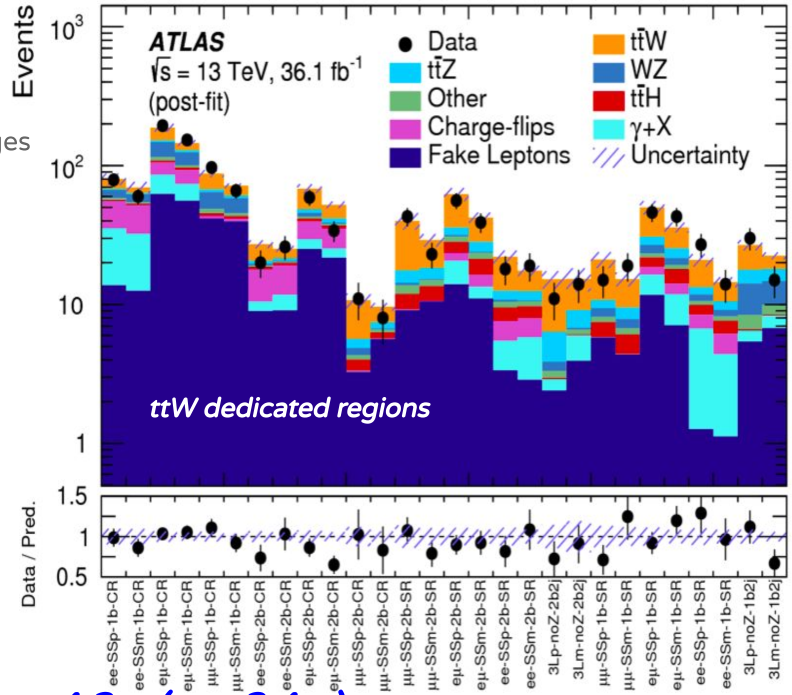


Anomalous couplings ? SMEFT



σ^{ttW} inclusive measurement

- Measured in 36.1 fb^{-1} together with ttZ cross-section
  - 2ℓ same-sign lepton (2ℓ-SS) and 3l regions enriched in ttW.
  - Both, veto on lepton pairs compatible with $|m_{\ell\ell} - m_Z| < 10$
  - 2ℓ separated by sign of leptons. 3ℓ, sign of the sum of lepton charges
- Fake background estimated (2ℓ) and WZ (3ℓ) in dedicated CRs
- Simultaneous fit of SR and CRs enriched in ttW to extract cross-section
  - Combined fit with ttZ enriched regions yield similar results.
  - Dominated by modelling and fake lepton statistics/modelling.



Uncertainty	$\sigma_{t\bar{t}Z}$	$\sigma_{t\bar{t}W}$
Luminosity	2.9%	4.5%
Simulated sample statistics	2.0%	5.3%
Data-driven background statistics	2.5%	6.3%
JES/JER	1.9%	4.1%
Flavor tagging	4.2%	3.7%
Other object-related	3.7%	2.5%
Data-driven background normalization	3.2%	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%

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	–

Significance = 4.3 σ (exp 3.4 σ)

$\sigma_{ATLAS}(ttW) = 0.87^{+0.13}_{-0.13}(stat)^{+0.14}_{-0.14}(syst)$ pb

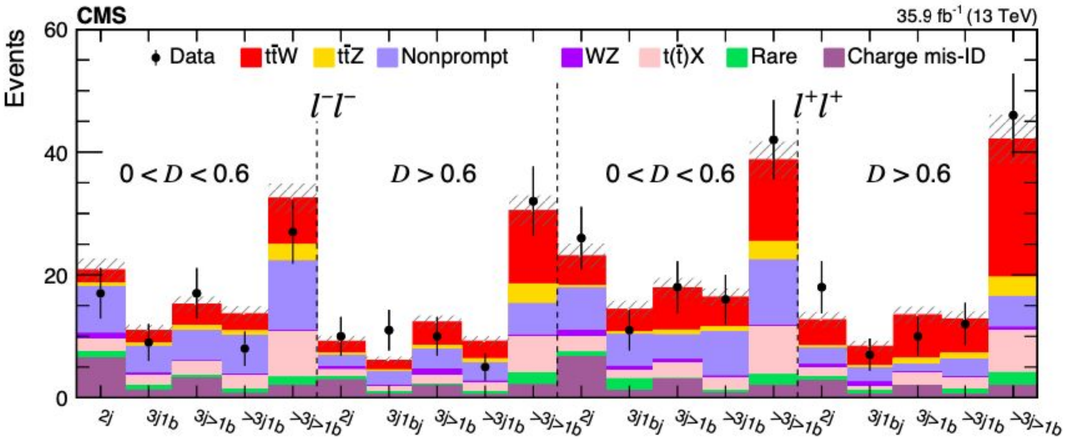
$\sigma_{theo}(ttW) = 0.60^{+0.08}_{-0.09}$ pb

arxiv:1610.07922 arxiv:1504.03446

JHEP 08 (2018) 011

σ^{ttW} inclusive measurement

- Measured in 35.9 fb^{-1} together with ttZ cross-section
  - Two lepton events same-sign lepton regions (2ℓ-SS) enriched in ttW.
  - 3ℓ and 4ℓ enriched in ttZ, similar to 77.5 fb-1 measurement.
- Two lepton enriched regions dominated by backgrounds:
  - Presenting fake leptons (Z+jets, *tt*) -> data-based fake-factors
  - Leptons with misidentified charge-> MC validated in data
- Inclusive ttW cross-section estimated fitting 2ℓ-SS regions and 3ℓ, 4ℓ
  - Separate strength parameters with ttW and ttZ.
  - ttW^+ (ttW^-) evaluated in $\ell^+\ell^+$ ($\ell^-\ell^-$) channels.



Source	Uncertainty from each source (%)	Impact on the measured tt̄W cross section (%)
Integrated luminosity	2.5	4
Jet energy scale and resolution	2–5	3
Trigger	2–4	4–5
B tagging	1–5	2–5
PU modeling	1	1
Lepton ID efficiency	2–7	3
Choice in μ_R and μ_F	1	<1
PDF	1	<1
Nonprompt background	30	4
WZ cross section	10–20	<1
ZZ cross section	20	—
Charge misidentification	20	3
Rare SM background	50	2
t(t̄)X background	10–15	4
Stat. unc. in nonprompt background	5–50	4
Stat. unc. in rare SM backgrounds	20–100	1
Total systematic uncertainty	—	14

$$\sigma(pp \to t\bar{t}W^+) = 0.58 \pm 0.09\,(\text{stat})^{+0.09}_{-0.08}\,(\text{syst})\,\text{pb},$$

$$\sigma(pp \to t\bar{t}W^-) = 0.19 \pm 0.07\,(\text{stat}) \pm 0.06\,(\text{syst})\,\text{pb}.$$

σ_{CMS} (ttW) = $0.77^{+0.12}_{-0.11}$(stat)$^{+0.13}_{-0.12}$(syst) pb

Significance = 5.3 σ (exp 4.5 σ)

σ_{theo} (ttW) = $0.60^{+0.08}_{-0.09}$ pb

arxiv:1610.07922 arxiv:1504.03446

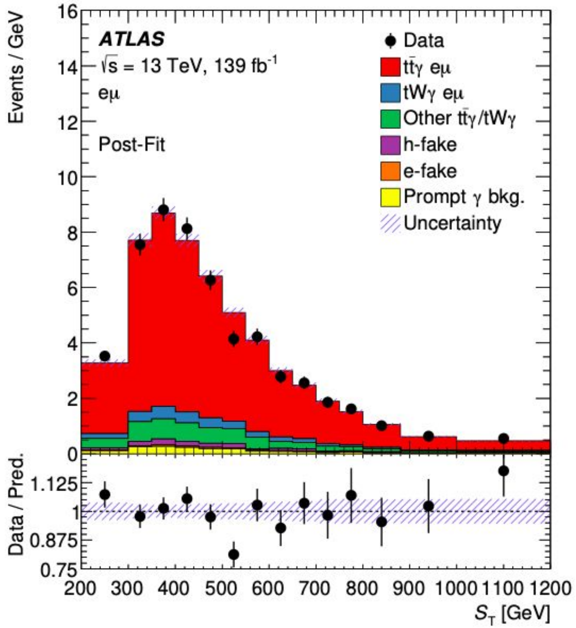
$\sigma^{tt\gamma} + \sigma^{tW\gamma}$ incl. and diff. measurement

- Measurement in the dilepton channel (eμ) with charged OS leptons.
  - One SR with requirement of 1 γ and 2 b-jets.
  - Well-separated objects are required $\Delta R(p_1,p_2) > 0.4$ *p= e,μ,γ,b_1,b_2*
- Selection dominated by signal, backgrounds (hadronic and electron fakes, prompt γ) from MC.
- Combined ttγ and tWγ process to extract its cross-section.
  - Fitting ST : scalar sum of p_T of all objects and p_T^{miss}.

Prefit, MC scaled to data

	Events
$t\bar{t}\gamma\ e\mu$	2391 ± 130
$tW\gamma\ e\mu$	156 ± 15
Other $t\bar{t}\gamma/tW\gamma$	279 ± 15
h-fake	78 ± 40
e-fake	23 ± 12
Prompt γ bkg.	87 ± 40
Total	3014 ± 160
Data	3014

Category	Uncertainty
$t\bar{t}\gamma/tW\gamma$ modelling	3.8%
Background modelling	2.1%
Photons	1.9%
Luminosity	1.8%
Jets	1.6%
Pile-up	1.3%
Leptons	1.1%
Flavour-tagging	1.1%
MC statistics	0.4%
Soft term E_T^{miss}	0.2%
$tW\gamma$ parton definition	2.8%
Total syst.	6.3%



$\sigma_{ATLAS}(tt\gamma+tW\gamma) = 39.^{+0.08}_{-0.08}(stat)^{+2.6}_{-2.2}(syst)$ fb

$\sigma^{fid}_{theo}(tt\gamma+tW\gamma) = 38.5^{+0.56}_{-2.18}(scale)^{+1.04}_{-1.18}(PDF)$ fb

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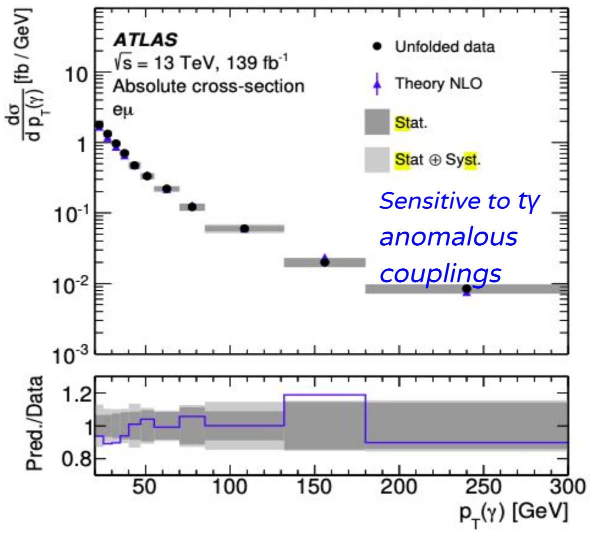
$\sigma^{tt\gamma} + \sigma^{tW\gamma}$ incl. and diff. measurement

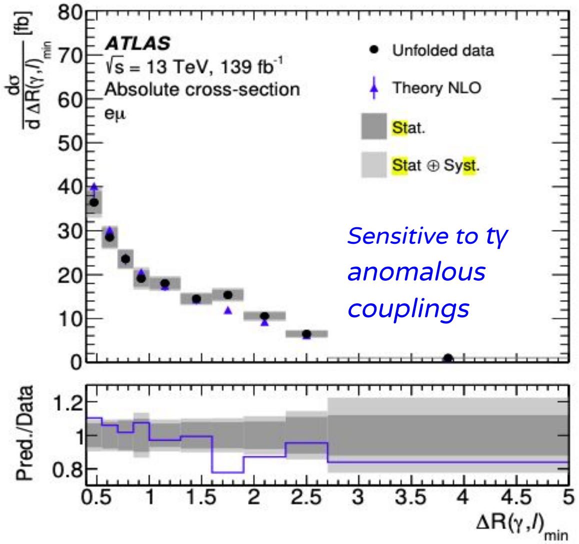
- Differential cross-section using iterative Bayesian unfolding.
- Absolute and normalized diff. cross-sections provided for:
  - p_T^{γ}, $|\eta_{\gamma}|$, $\Delta R(\gamma,\ell)_{min}$: sensitive to tγ coupling structure
  - $\Delta\phi(\ell,\ell)$, $|\eta_{\ell\ell}|$: sensitive to *tt* spin correlation
- Good agreement between theory NLO predictions and unfolded data
  - MG5@NLO +Py8 and HW7 predictions slightly worse than theory

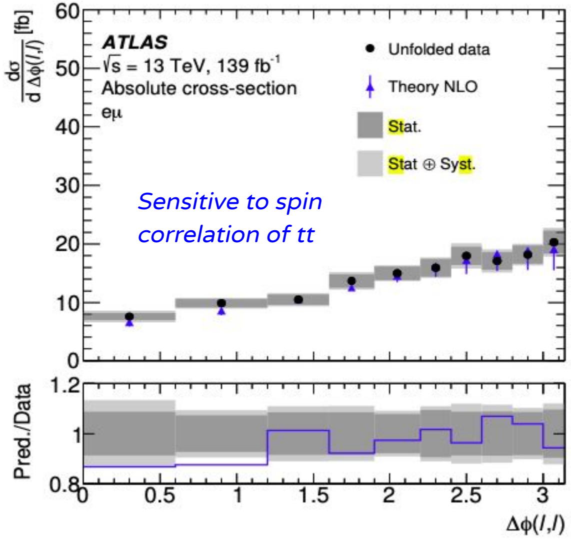
Table 3: χ^2/ndf and p-values between the measured absolute cross-sections and the NLO calculation.

Predictions	$p_T(\gamma)$		$\|\eta(\gamma)\|$	
	χ^2/ndf	p-value	χ^2/ndf	p-value
Theory NLO	6.1/11	0.87	4.5/8	0.81

Predictions	$\Delta R(\gamma,\ell)_{min}$		$\Delta\phi(\ell,\ell)$		$\|\Delta\eta(\ell,\ell)\|$	
	χ^2/ndf	p-value	χ^2/ndf	p-value	χ^2/ndf	p-value
Theory NLO	11.7/10	0.31	5.8/10	0.83	6.2/8	0.62

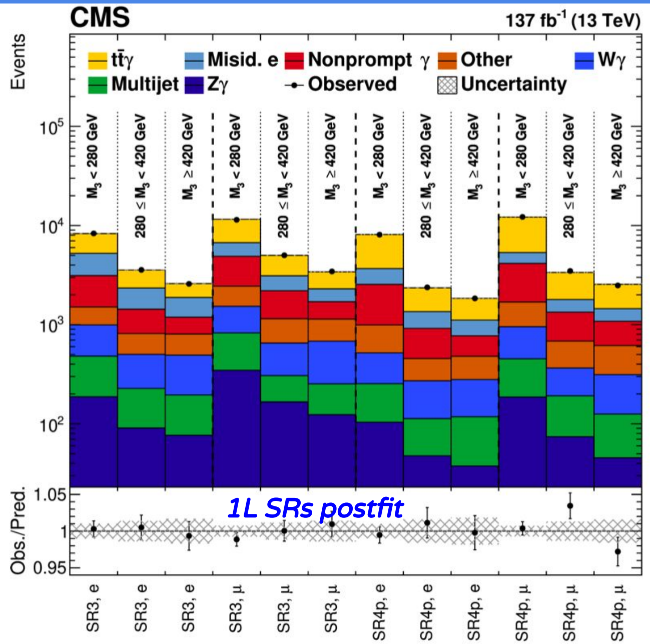


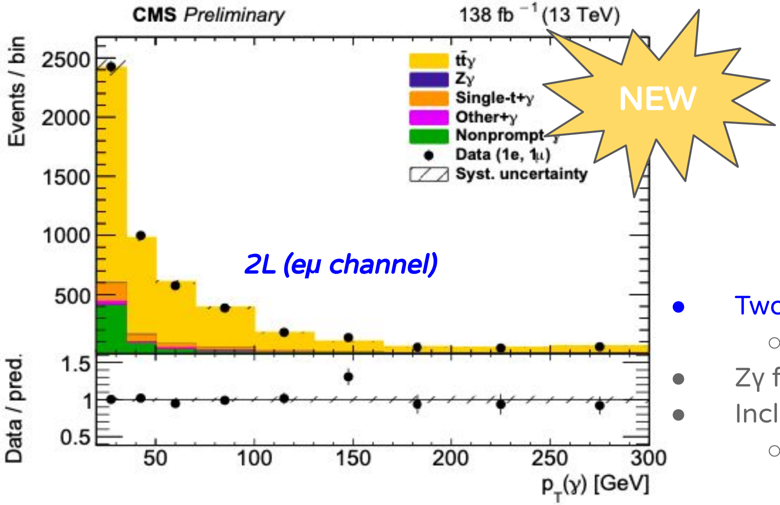




$\sigma^{tt\gamma}$ incl. and diff. measurement in 1ℓ and 2ℓ

- One-lepton channel: 1ℓ, at least 3 jets (at least 1 b-tagged), 1γ
    - SR3 (N_j = 3) and SR4p (N_j>=4). Photon must be central ($|\eta_\gamma|$<1.44)
- Non-prompt photons and misidentified electrons dominate
    - Non-prompt γ is data-driven
    - misidentified electrons estimated from DY enriched CRs.
- Vγ and multijet constrained in dedicated control regions
- Inclusive fit of SR3 and SR4p and their CRs to extract normalization of ttγ.
    - Dominant uncertainties are Wγ and non-prompt background normalizations



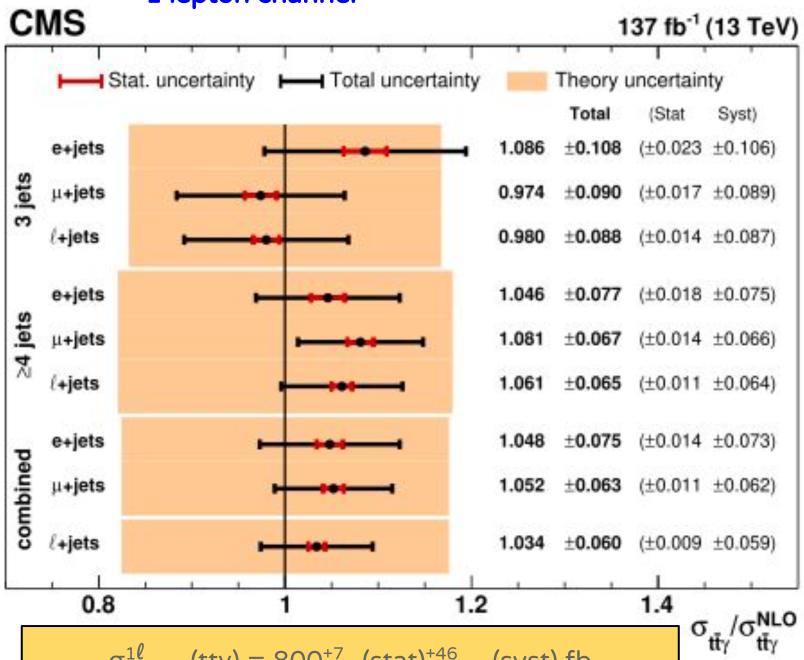


- Two-lepton channel: 2ℓ (opposite charge), at least 1 b-jet and 1γ
    - Veto if $|m_{\ell\ell} - m_Z|$ < 15 GeV and $|m_{\ell\ell\gamma} - m_Z|$ < 15 GeV
- Zγ from dedicated CR. Non-prompt γ background from data-driven method
- Inclusive cross-section derived from template fit on $p_T(\gamma)$.
    - Dominant uncertainties are signal modelling and experimental uncs.

$\sigma^{tt\gamma}$ incl. and diff. measurement in 1ℓ and 2ℓ

NEW

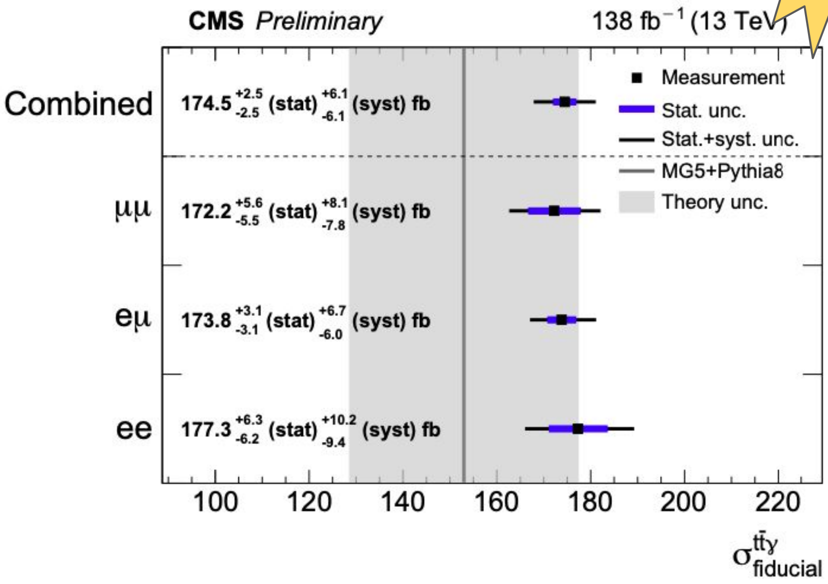
1 lepton channel



$\sigma^{1\ell}_{CMS}(tt\gamma) = 800^{+7}_{-7}(stat)^{+46}_{-46}(syst)$ fb

$\sigma^{fid,NLO}_{theo}(tt\gamma) = 773^{+135}_{-135}$ fb

2 lepton channel



$\sigma^{2\ell}_{CMS}(tt\gamma) = 174.4^{+2.5}_{-2.5}(stat)^{+6.1}_{-6.1}(syst)$ fb

$\sigma^{fid}_{theo}(tt\gamma) = 153^{+25}_{-25}$ fb arXiv:2107.01508

CMS-PAS-TOP-21-004

$\sigma^{tt\gamma}$ incl. and diff. measurement in 1ℓ and 2ℓ

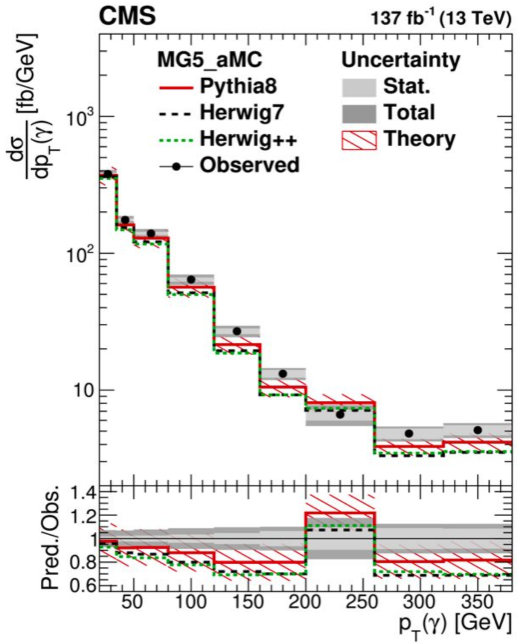
NEW

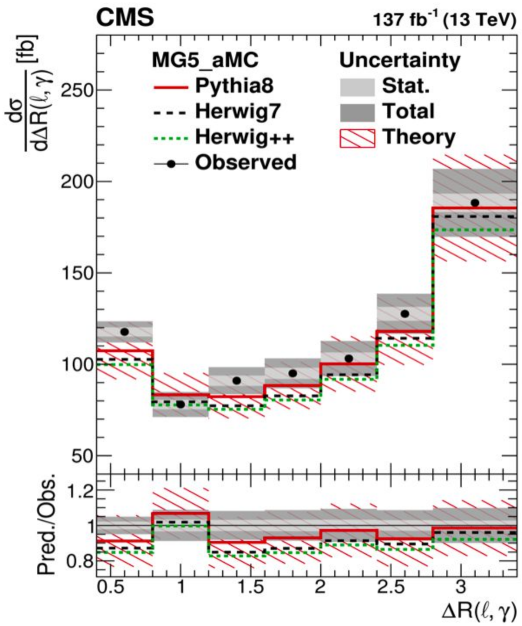
1 lepton channel

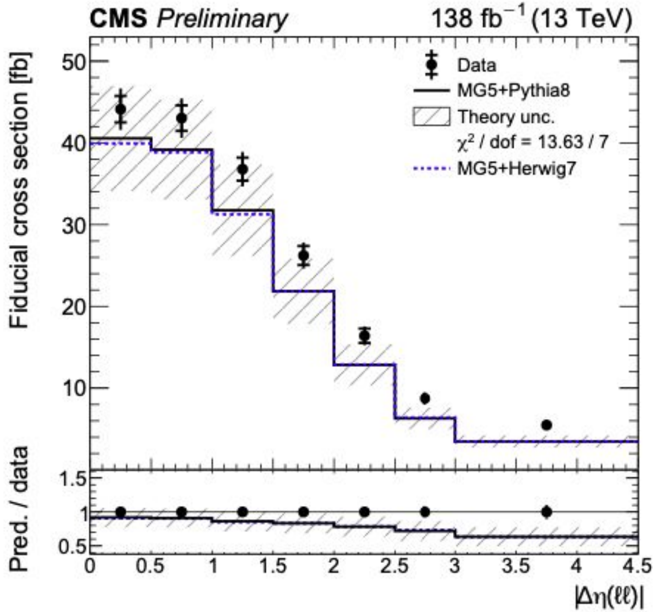
- Particle-level unfolded distributions. Iterative Bayesian.
- Good agreement within uncertainties comparing MG5 and some shower models. Agreement evaluated through χ^2

2 lepton channel

- Particle-level unfolded distributions
- Good agreement within uncertainties evaluated through χ^2



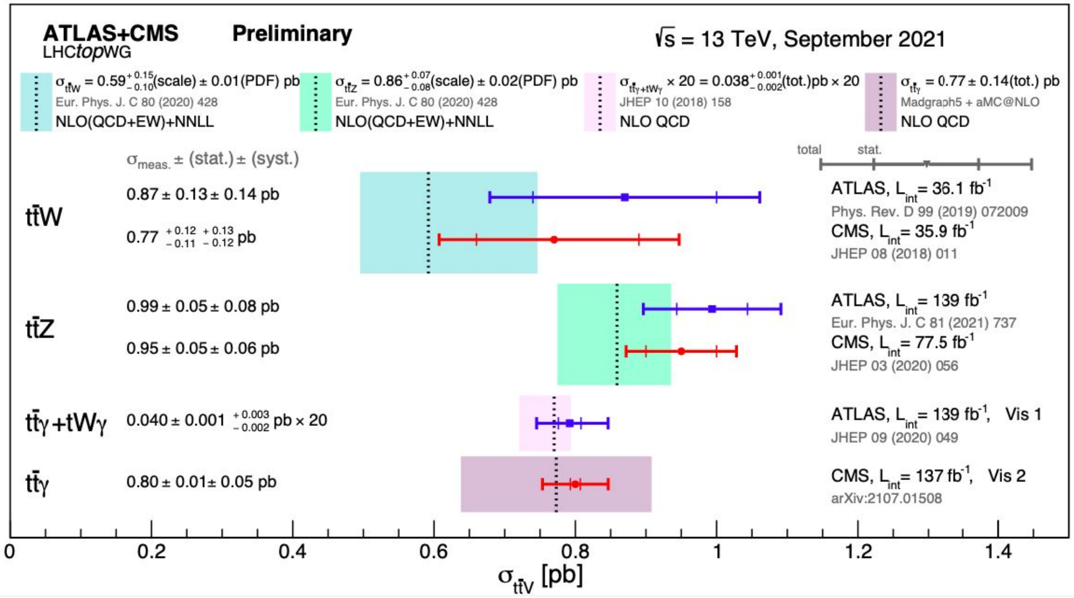




Conclusions

- LHC Run-2 data and new techniques allowed to improve sensitivity to t(t)V measurements.
- Inclusive and differential cross-sections computed for several processes
- No observation beyond SM expectation observed so far
- Analysis become systematics dominated

LHC Run-3 is coming ! More results are coming! Stay tuned !

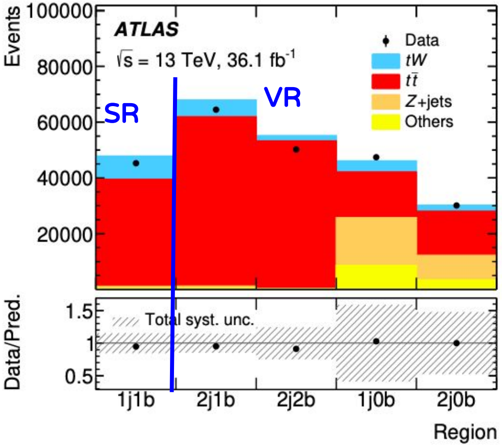


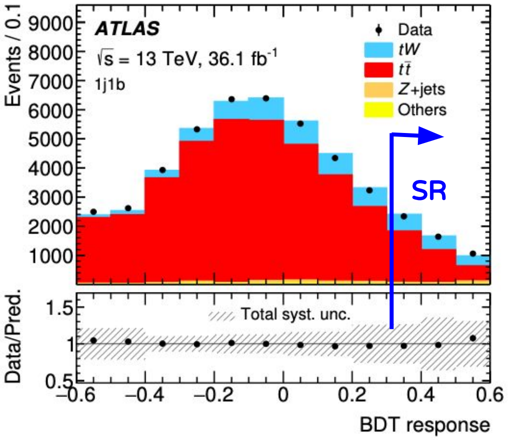
LHC TopWP Summary Plots

Additional material

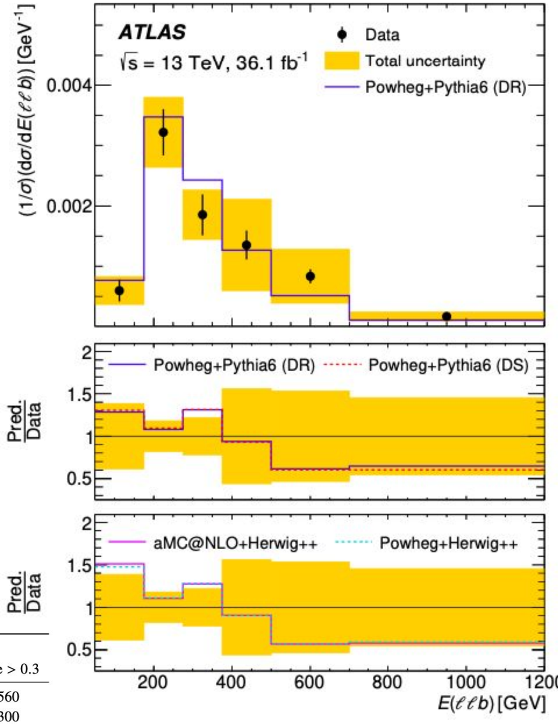
σ^{tW} incl. and diff. measurements

- Measurement performed in 2ℓ signal with OS charged leptons.
- Signal region with exactly 1 jet required to be b-tagged and large p_T^{miss}.
  - Additional regions to validate background model.
- Dominated by tt background -> Separation achieved by BDT > 0.3
  - Trained on objects combined kinematics and event-level variables
  - Reducing uncertainties thanks to reduction of ttbar
- Differential cross-sections obtained using Iterative Bayesian unfolding
  - E(b), $m_T(\ell\ell\nu\nu b)$, E(llb), $m(\ell_1,b)$, $m(\ell_2,b)$, $m(\ell\ell b)$
  - Models use show a lower number of predicted events at high-momentum



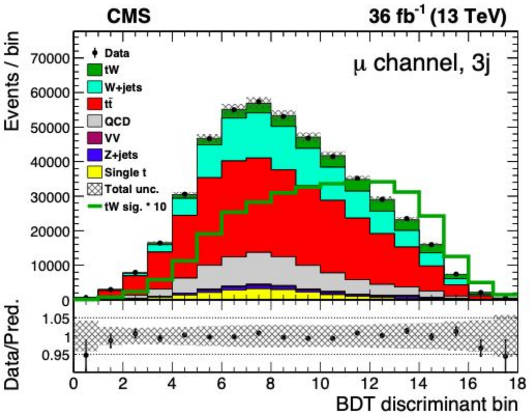


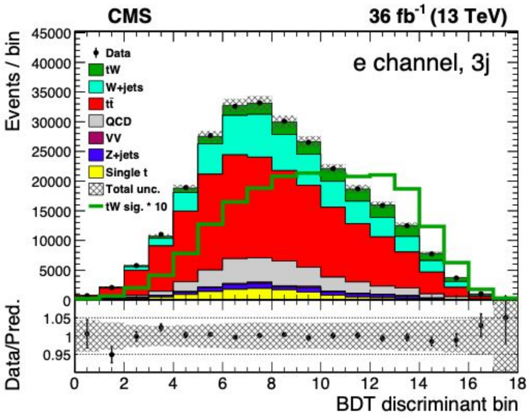
Process	Events	Events BDT response > 0.3
tW	8 300 ± 1 400	1 970 ± 560
$t\bar{t}$	38 400 ± 6 600	3 400 ± 1 300
Z + jets	620 ± 310	159 ± 80
Diboson	230 ± 58	81 ± 20
Fakes	220 ± 220	19 ± 19
Predicted	47 800 ± 7 300	5 600 ± 1 700
Observed	45 273	5 043



σ^{tW} incl. measurements

- Measurement in 1l signal region and 3 jets (exactly one b-jet)
  - Control regions with 2j (W+jets, QCD) and 4j (ttbar).
- BDT to separate *tW* and *tt*.
  - Well-modelled kinematic and event-level variables.
  - Trained separately for electron and muon channels
- Simultaneous fit of both lepton channels and CRS for cross-section on BDT templates.
  - Dominated by QCD normalization and jet calibration uncertainties





Source	Relative uncertainty (%)
Experimental	
Jet energy scale	6
b tagging efficiency	4
Luminosity	3
Lepton energy scale	2
Trigger efficiency	1
Jet energy resolution	1
b tagging misidentification rate	<1
Unclustered energy	<1
Pileup	<1
Normalization	
QCD multijet normalization	7
W+jets normalization	6
Z+jets normalization	3
Single t normalization	1
$t\bar{t}$ normalization	1
VV normalization	<1
Theoretical	
h_{damp}	4
Diagram removal/diagram subtraction	3
Underlying event tune	3
Colour reconnection model	1
Parton distribution function	1
Matrix element/parton shower matching	1
Final-state radiation	<1
Initial-state radiation	<1
Total systematic uncertainty	14
Statistical uncertainty	5
Total uncertainty	15

σ_{CMS} (tW) = 89^{+4}_{-4}(stat)$^{+12}_{-12}$(syst) pb

σ^{th}_{NLO} = $71.7^{+1.8}_{-1.8}$(scale)$^{+3.4}_{-3.4}$(PDF) pb

σ^{th}_{NNLO} = $79.5^{+1.9}_{-1.8}$(scale)$^{+2.0}_{-1.4}$(PDF) pb