ATLAS $t\bar{t}\gamma$ and $t\bar{t}Z$ joint EFT interpretation

arXiv:2403.09452

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on behalf of the ATLAS Collaboration
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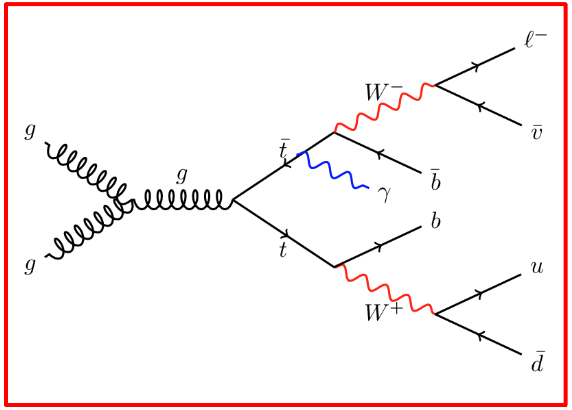
Joint session of the LHC EFT and Top Working Groups

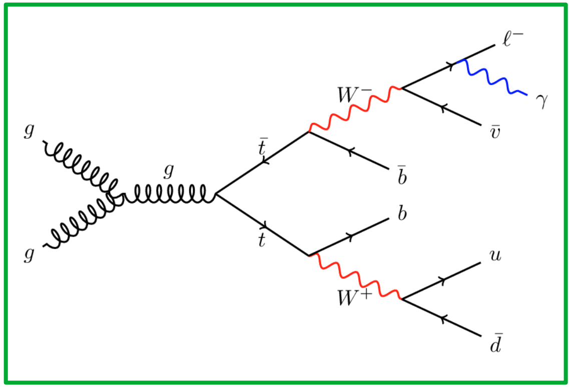
FSP ATLAS
Erforschung von Universum und Materie

CPPS Center for Particle Physics Siegen

Motivation for $t\bar{t}\gamma$

- Several contributions to final states with top quarks and photons
  - $t\bar{t}\gamma$ production: Radiative top production
    - Photon emitted from ISR or from off-shell top quarks
  - $t\bar{t}\gamma$ decay: Radiative top decay
    - Photon from on-shell top quark or its decay products
  - Negligible interference between production and decay in narrow width approximation: JHEP03(2020)154
- Radiative production probes $t\gamma$ coupling
- **Sensitive to new physics: anomalous electromagnetic dipole moments of top quark and interpretation in context of EFT (C_{tB}, C_{tW})**



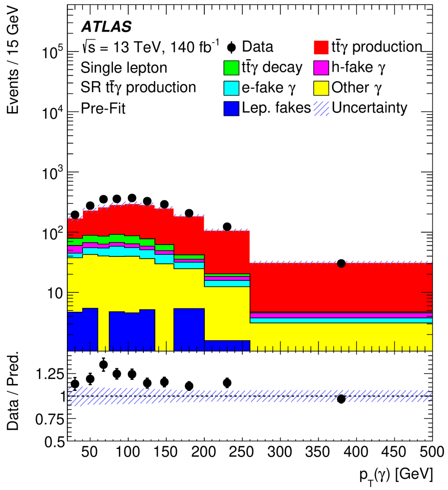


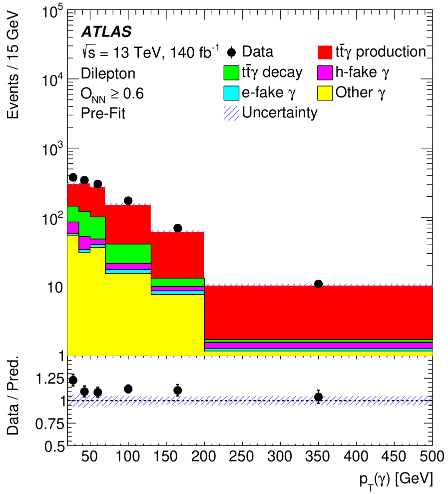
Scope of the measurements

- Differential and inclusive $t\bar{t}\gamma$ cross-section in single-lepton and dilepton channel at particle level in a fiducial phase space
  - Focusing on $t\bar{t}\gamma$ production only
    - Treating events where photon is emitted from decay products as background
    - Used to extract limits on C_{tB} and C_{tW} EFT operators
  - Measurement of *standard* $t\bar{t}\gamma$ process (production+decay)
    - $t\bar{t}\gamma$ regardless of photon origin
- EFT interpretation
  - Differential photon p_T cross-section used to set limits on C_{tB} and C_{tW}
  - Limits from simultaneous measurement of photon p_T in $t\bar{t}\gamma$ and Z p_T in $t\bar{t}Z$
  - Same object selection and systematic uncertainties scheme as $t\bar{t}Z$ (arXiv:2312.04450) to allow for combination for EFT interpretation

Event selection and background

- Event selection: $t\bar{t}$ in single-lepton or dilepton channel and exactly one photon
- Signal: $t\bar{t}\gamma$ production, MG5_aMC@NLO+Pythia8 NLO
- Background:
  - $t\bar{t}\gamma$ decay MG5_aMC@NLO+Pythia8 LO
    - NLO/LO k factor applied
  - Prompt photon background
    - Wγ, Zγ, single-top quark, diboson $t\bar{t}$+V with photon from shower
  - Fake photon
    - electronic fakes e→γ (Z→eγ/Z→ee CR)
    - hadronic fakes h→ γ (ABCD method)
  - Fake leptons (matrix method)





Analysis strategy

- Neural network (NN) to define $t\bar{t}\gamma$ enriched signal region (SR) and background enriched control regions (CR)
- Single-lepton channel:
  - Four class NN: $t\bar{t}\gamma$ production, $t\bar{t}\gamma$ decay, photon fakes and other γ
  - NN output used to define a $t\bar{t}\gamma$ production SR and 3 CRs
- Dilepton channel:
  - Binary classification $t\bar{t}\gamma$ production vs. all backgrounds
  - NN output distribution used as input distribution for profile-likelihood fit and to define 2 regions for the differential cross-sections
- Inclusive cross-section measurement: profile-likelihood fit in the SRs and CRs simultaneously
- Differential cross-section: profile-likelihood unfolding (unregularised) in the same regions in the single-lepton channel and in 1 SR and 1 CR in the dilepton channel

Fiducial measurements at particle level

- **Inclusive cross section**
  - $t\bar{t}\gamma$ production, $t\bar{t}\gamma$ decay as free floating parameter
  - total $t\bar{t}\gamma$ (production+decay), 20% normalisation uncertainty on $t\bar{t}\gamma$ decay
- **Differential measurements**
  - p_T & $|\eta|$ of photon, $\Delta R(\gamma,b)_{min}$, $\Delta R(\gamma,l)_{min}$, $\Delta R(\gamma,l)$, $\Delta R(j,l)_{min}$, $p_T(j_1)$
  - Additional in dilepton: $\Delta\phi(l,l)$, $|\Delta\eta(l,l)|$, $\Delta R(\gamma,l_1)$, $\Delta R(\gamma,l_2)$, $p_T(l_1,l_2)$

Fiducial phase space at particle level:

- Exactly one isolated γ
  - $p_T > 20$GeV, $|\eta| < 2.37$
  - p_T of charged particles within $\Delta R < 0.2$ less than 5% of $p_T(\gamma)$
- Exactly 1 (2) leptons
  - $p_T > 25$GeV, $|\eta| < 2.5$
- At least 4 (2) jets
  - $p_T > 25$GeV, $|\eta| < 2.5$
  - At least 1 b jet via ghost matching
- $\Delta R(l,\gamma) > 0.4$

Inclusive cross-section $t\bar{t}\gamma$ production

	Fiducial cross section (fb)
Combined	322 ±5(stat) ±15(syst) (5.2%)
	NLO MC: 299 ±31(scale+PDF)
Single lepton	290 ±5(stat) ±20(syst) (7.7%)
Dilepton	46.5 ±1.4(stat) ±2.9(syst) (7.8%)

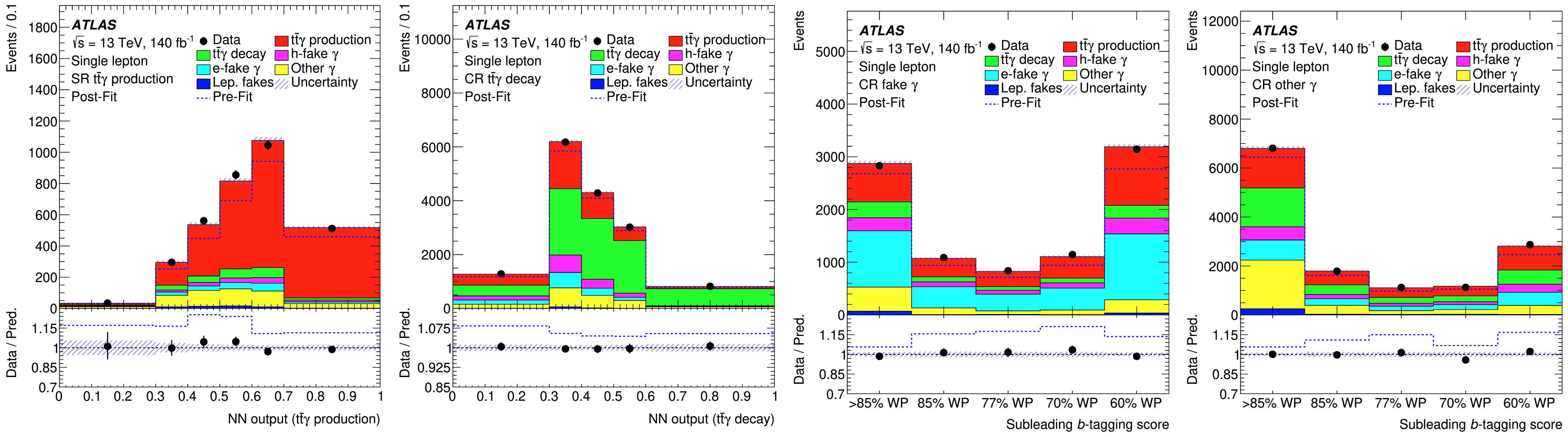
- Measured cross-section slightly larger than MC prediction
- Uncertainties dominated by $t\bar{t}\gamma$ modelling
- Combination of channels reduces impact of jet and b-tagging uncertainties
- $t\bar{t}\gamma$ production parton shower (PS) uncertainty has different correlation between channels

→ Total cross-section in backup

Source	$\Delta\sigma_{t\bar{t}\gamma\text{ production}}/\sigma_{t\bar{t}\gamma\text{ production}}$ (%) Single lepton	Dilepton	Combination
Statistical uncertainty	1.8	3.3	1.5
MC statistical uncertainties	1.5	1.5	1.0
Modelling uncertainties			
$t\bar{t}\gamma$ production PS uncertainty	2.4	3.7	0.9
Other $t\bar{t}\gamma$ production modelling	5.1	1.6	3.0
$t\bar{t}\gamma$ decay modelling	0.3	1.3	0.8
$t\bar{t}\gamma$ decay normalisation	2.4	3.1	2.1
Prompt photon background normalisation	1.5	2.0	2.0
Fake photon background estimate	0.8	1.5	1.6
Fake lepton background estimate	0.4	–	0.1
Other Background modelling	0.7	0.2	0.5
Experimental uncertainties			
Jet uncertainties	3.5	3.0	1.7
B-tagging uncertainties	2.6	2.1	1.0
Photon	0.5	1.5	0.8
Lepton	1.3	1.4	1.3
E_{T}^{miss}	0.3	0.4	0.4
Pile-up	0.3	0.7	0.5
Luminosity	0.8	1.0	0.8
Total systematic uncertainty	7.6	7.1	5.0
Total uncertainty	7.8	7.7	5.2

Post-fit distributions input variables

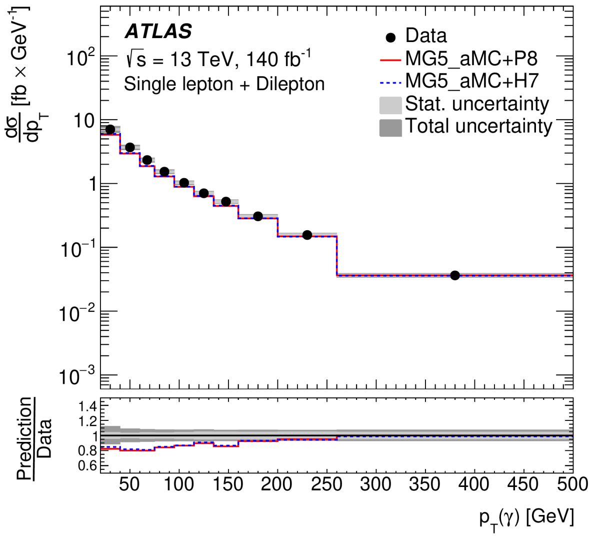
Post-fit distributions of the input variables to the single-lepton channel

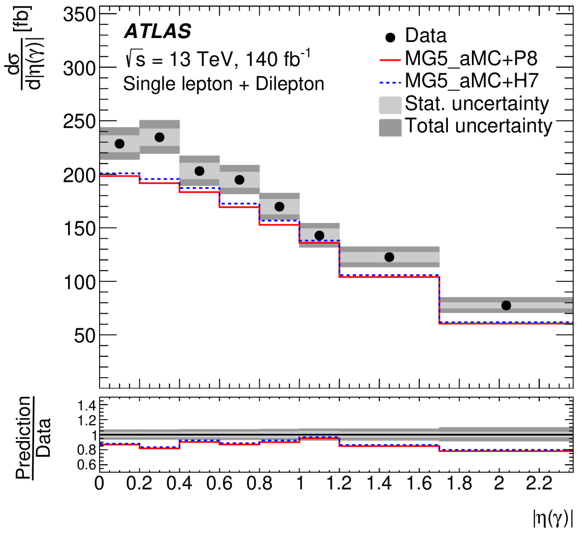


$t\bar{t}\gamma$ production: differential cross-section

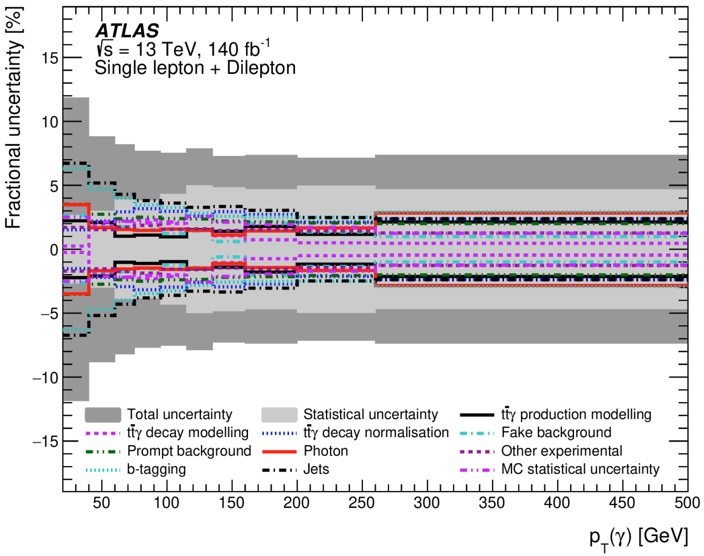
Single lepton+Dilepton

Absolute





- Shape generally well described by MC, measured cross-section larger than prediction, as seen in inclusive cross-section
- Uncertainties 8-10% for absolute cross-section and 5% for normalized cross-section
- Large contribution from jets, b-tagging and statistical uncertainty



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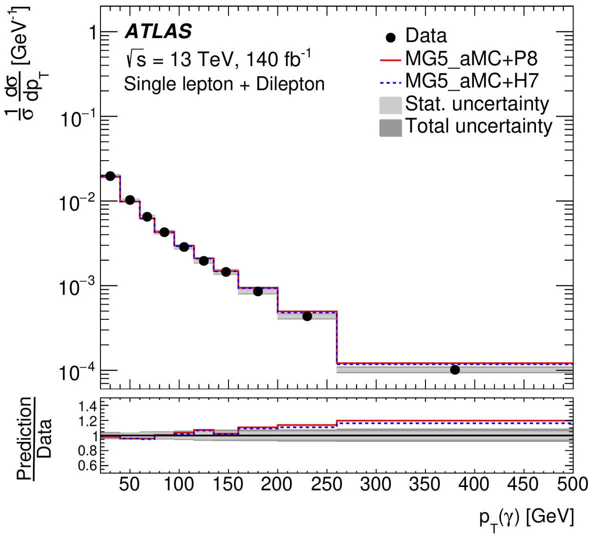
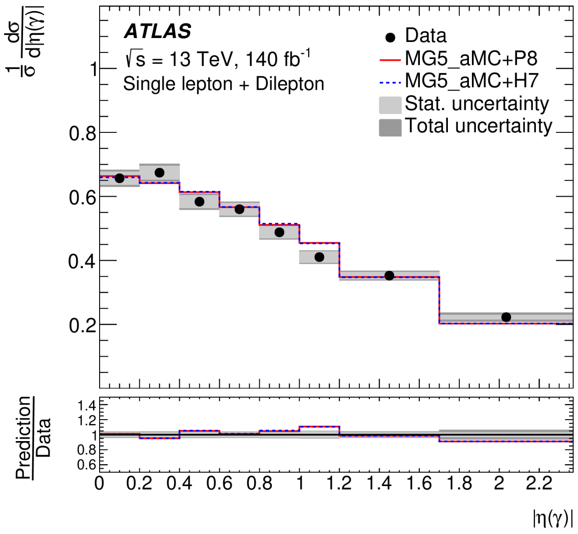
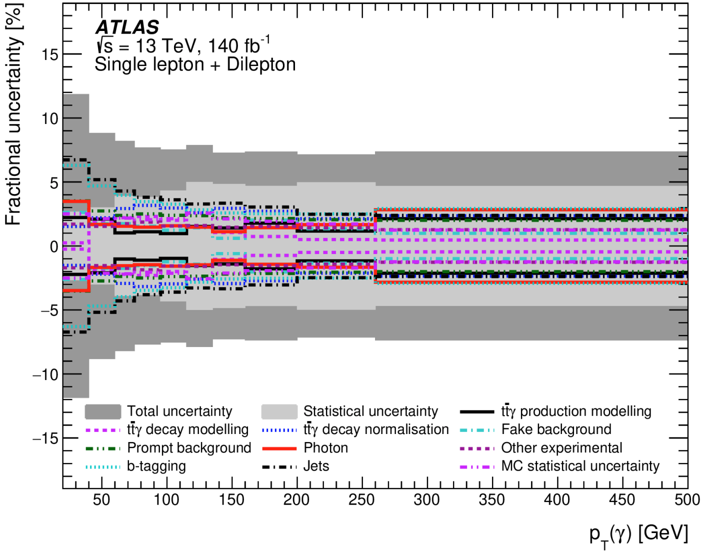
Normalised



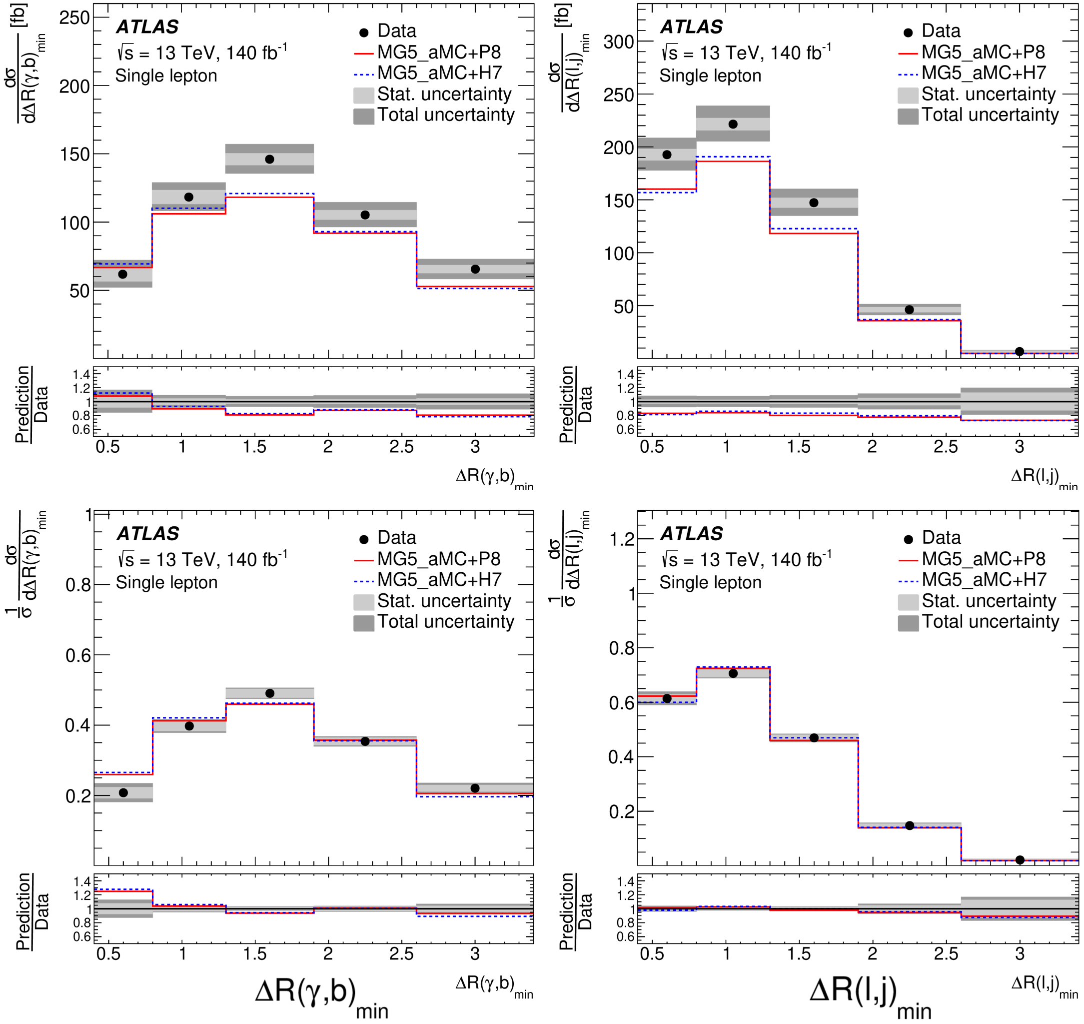




$t\bar{t}\gamma$ production: Single-lepton channel

Absolute

Normalised

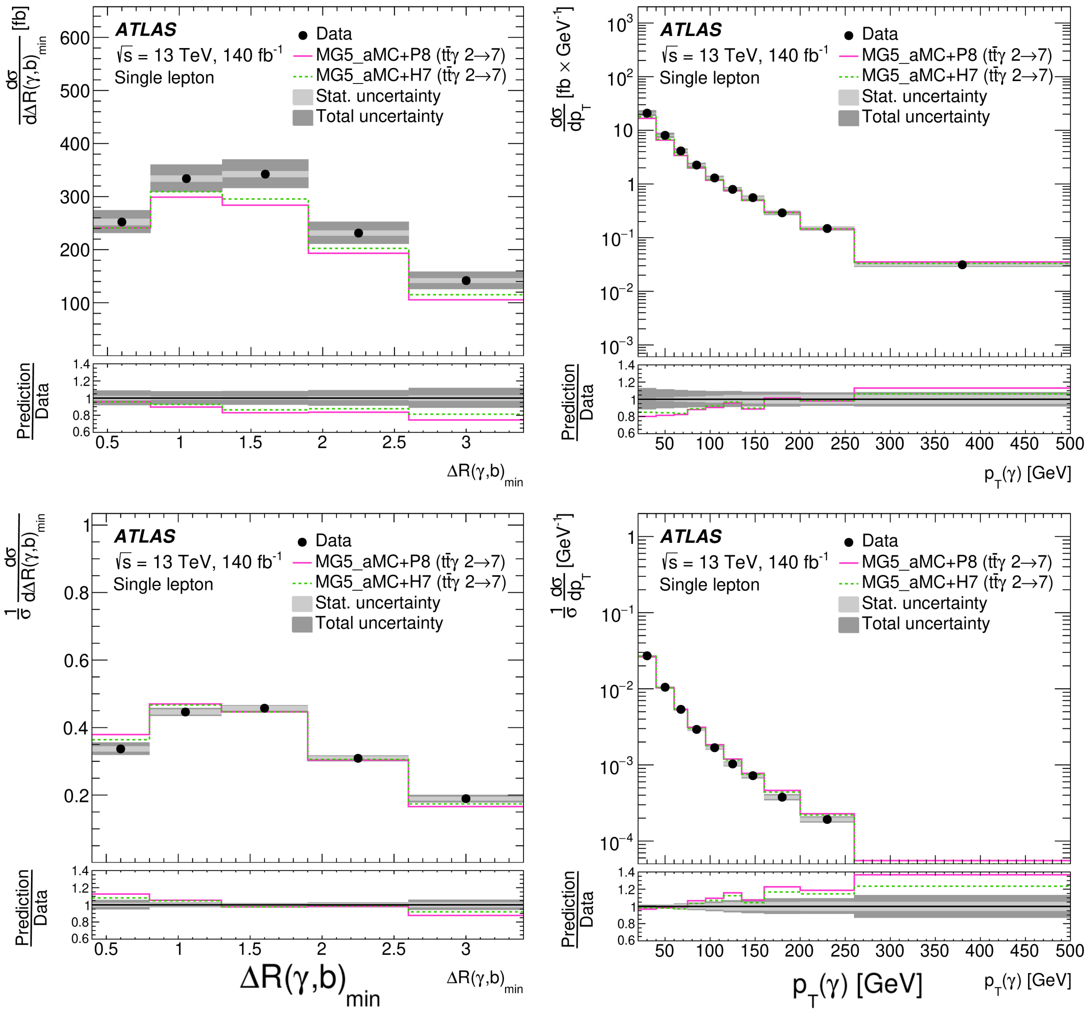


- Examples of angular variables
- Shape of measured cross-sections in general well described by MC
- Measured cross-section slightly larger than MC prediction
- Similar agreement in dilepton channel

$t\bar{t}\gamma$ total: Single-lepton channel

Absolute

Normalised

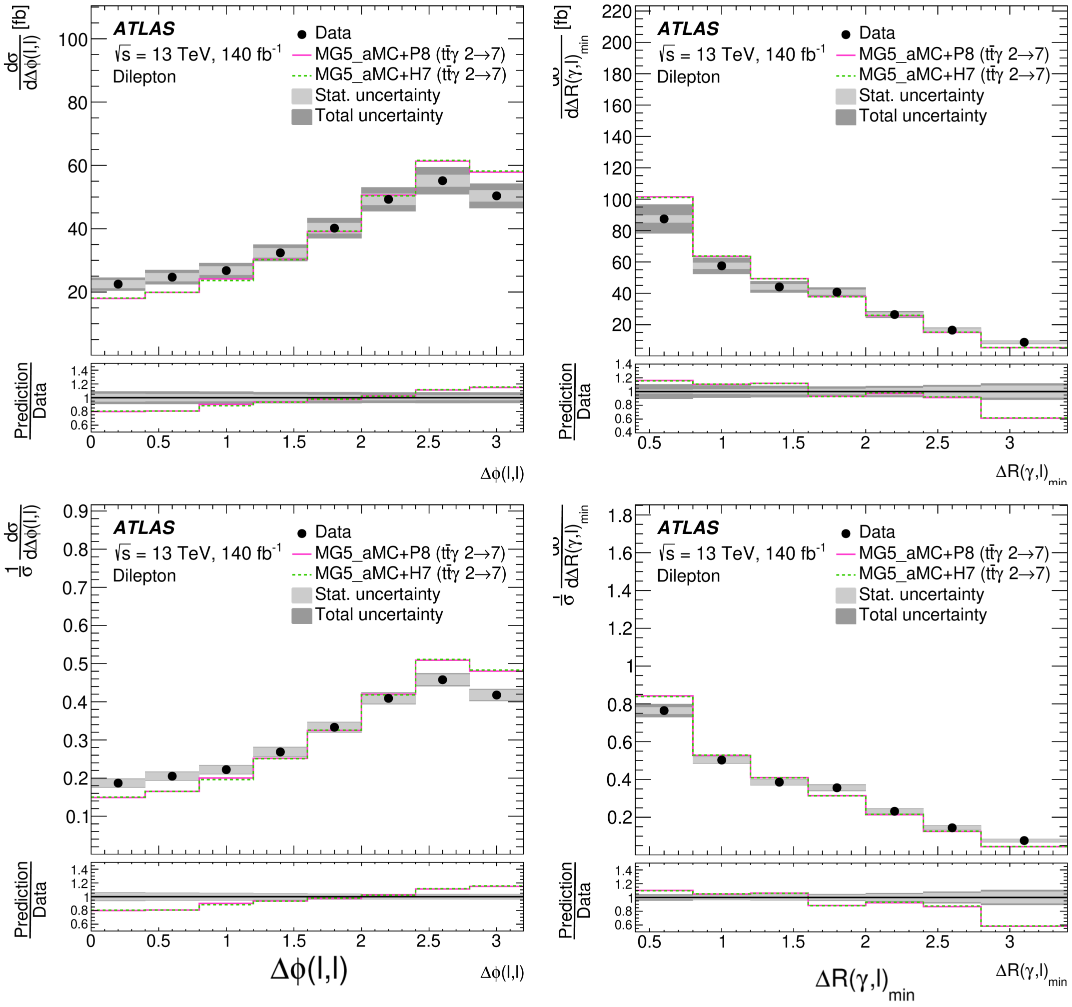


- The MC prediction is simulated as doubly resonant 2→7 process at LO accuracy
- Measured cross-section slightly larger then MC prediction

$t\bar{t}\gamma$ total: Dilepton channel

Absolute

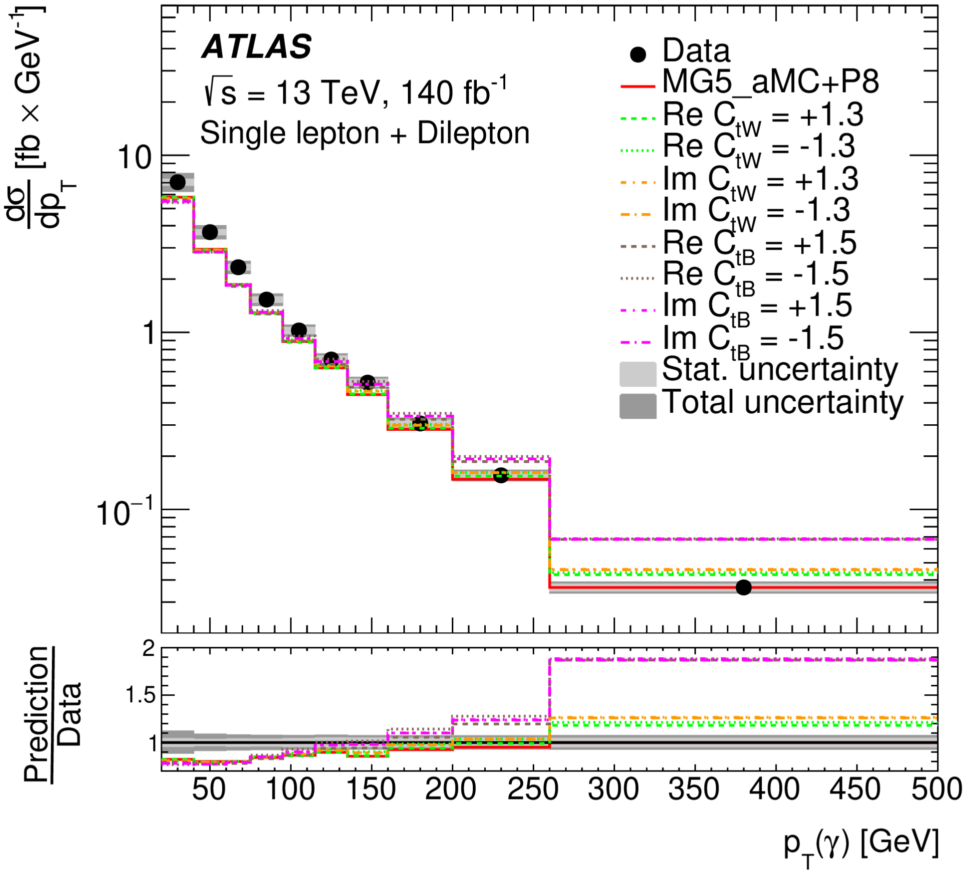
Normalised



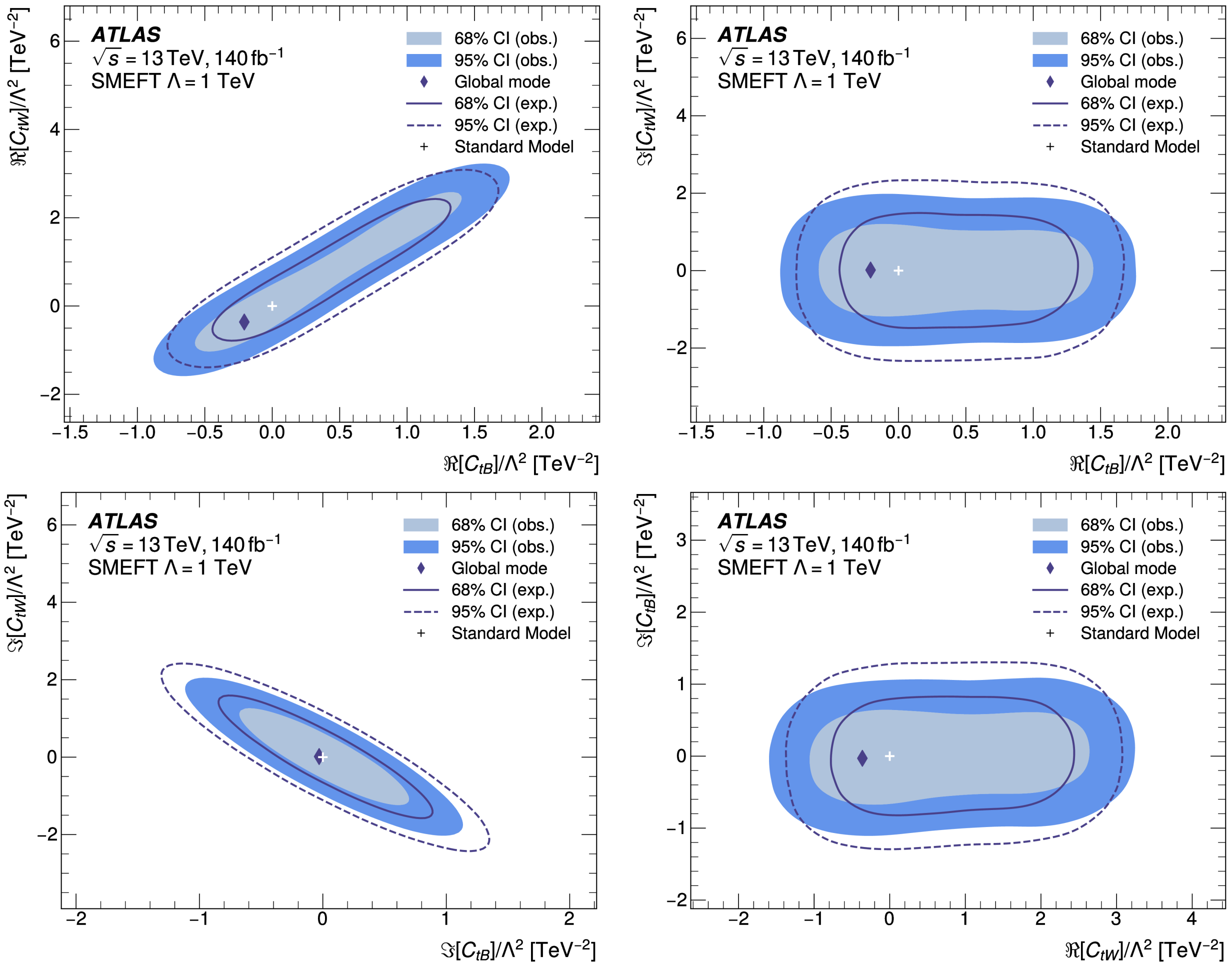
- Shape of angular variables in dilepton channel well described except for $\Delta\phi(l,l)$
  - Difference to MC for $\Delta\phi(l,l)$ observed in previous analysis of $t\bar{t}\gamma$ and $t\bar{t}$ as well
- Observed cross-section larger than MC prediction
- Same binning as in CMS paper JHEP 05 [2022] 091

EFT interpretation

- Most sensitive observable is photon p_T, using combination of single lepton and dilepton
- Relevant dim 6 Wilson coefficients in Warsaw basis: C_{tB}, C_{tW}, also extracted in terms of C_{tW}, C_{tZ} and C_{tZ}, $C_{t\gamma}$
- Produced using SMEFTsim 3.0 model using alternative weights to simulate EFT effects
- EFT samples at LO, reweighted to NLO using k factor (bin by bin)



Limits on C_{tB}, C_{tW} from $t\bar{t}\gamma$ production

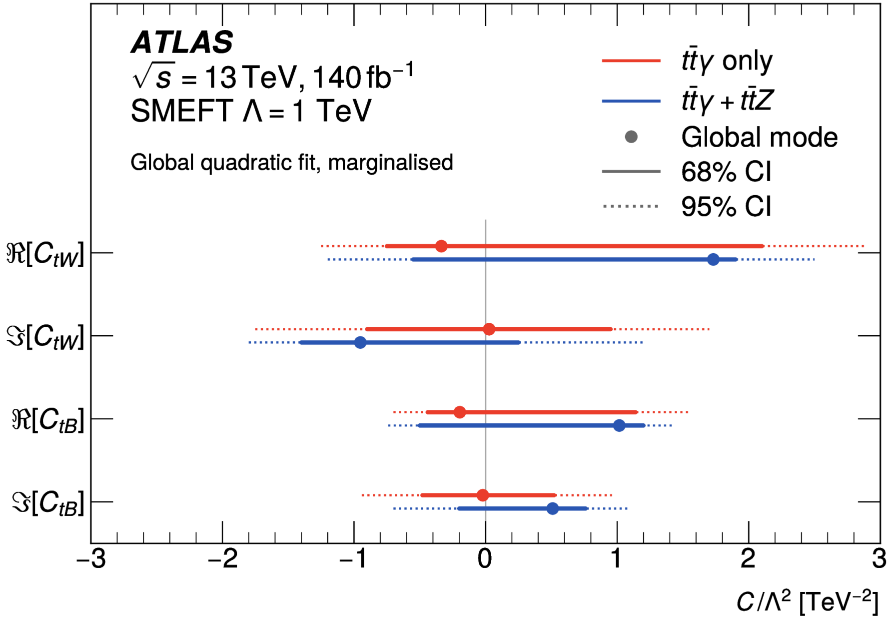


- Simultaneous extraction of real and imaginary part of C_{tB}, C_{tW}
- Shown are some of the marginalised 2D distributions
- Stronger constraints on C_{tB} than on C_{tW}
- Results are in agreement with Standard Model

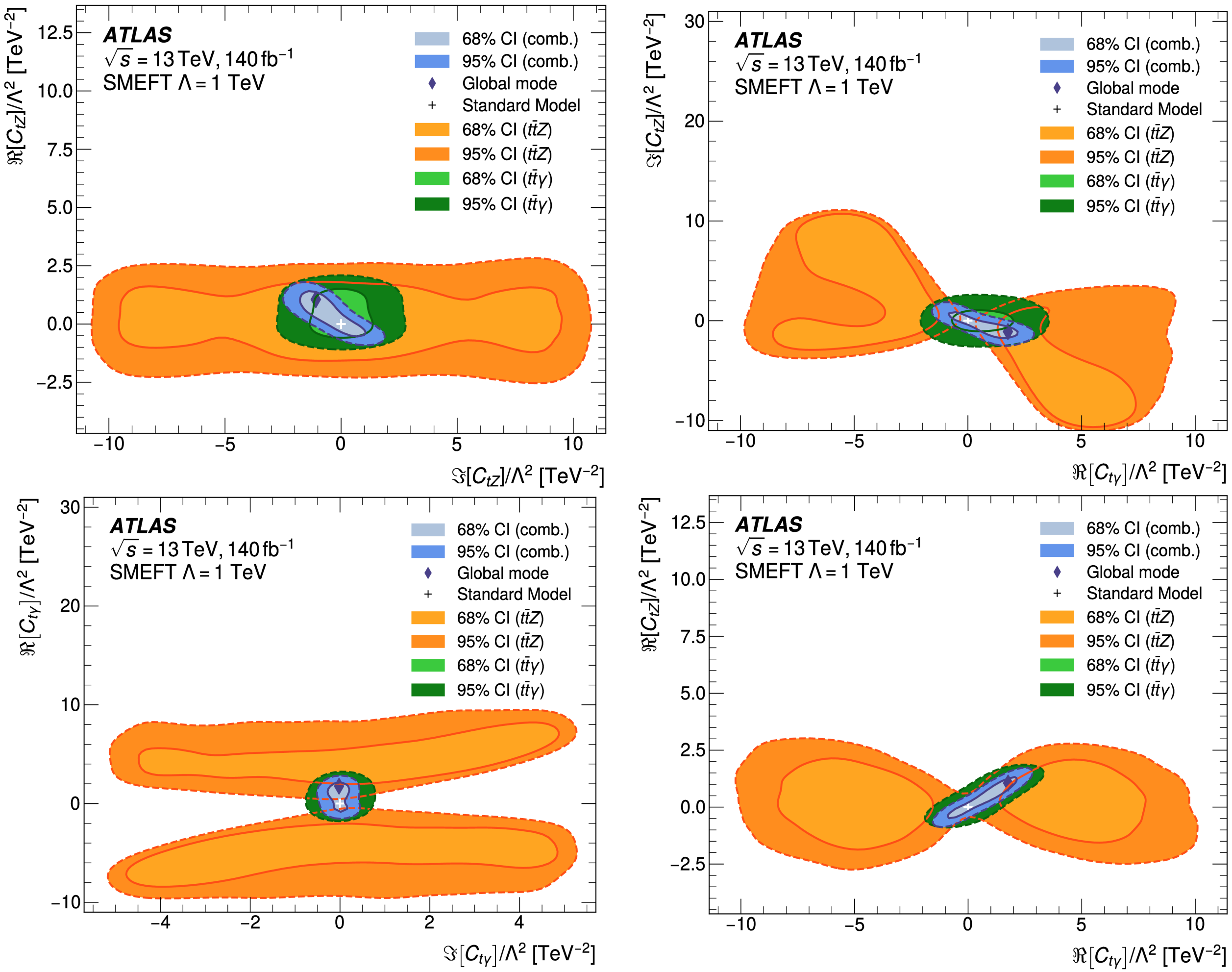
Combination of $t\bar{t}\gamma$ and $t\bar{t}Z$

- $t\bar{t}\gamma$ and $t\bar{t}Z$ are complementary:
  - Limits obtained from simultaneous profile-likelihood unfolding of photon and Z p_T in all SRs and CRs of the analyses
  - Yields tighter limits, especially in C_{tW}

Wilson coefficient		68% CI (exp.)	95% CI (exp.)	68% CI (obs.)	95% CI (obs.)	Best-fit
$\Re[C_{tW}]$	$O(\Lambda^{-4})$ (marg.)	[−0.65, 1.2]	[−1.1, 2.3]	[−0.55, 1.9]	[−1.2, 2.5]	1.73
	$O(\Lambda^{-4})$ (indep.)	[−0.48, 0.54]	[−0.82, 0.88]	[−0.30, 0.32]	[−0.56, 0.60]	0.01
$\Im[C_{tW}]$	$O(\Lambda^{-4})$ (marg.)	[−1.1, 0.50]	[−1.9, 1.4]	[−1.4, 0.25]	[−1.8, 1.2]	−0.96
	$O(\Lambda^{-4})$ (indep.)	[−0.54, 0.50]	[−0.86, 0.84]	[−0.32, 0.30]	[−0.60, 0.58]	−0.01
$\Re[C_{tB}]$	$O(\Lambda^{-4})$ (marg.)	[−0.36, 0.74]	[−0.68, 1.3]	[−0.48, 1.2]	[−0.74, 1.4]	1.01
	$O(\Lambda^{-4})$ (indep.)	[−0.33, 0.33]	[−0.56, 0.55]	[−0.25, 0.20]	[−0.43, 0.39]	−0.04
$\Im[C_{tB}]$	$O(\Lambda^{-4})$ (marg.)	[−0.38, 0.66]	[−0.86, 1.1]	[−0.20, 0.76]	[−0.70, 1.1]	0.52
	$O(\Lambda^{-4})$ (indep.)	[−0.35, 0.33]	[−0.57, 0.55]	[−0.24, 0.22]	[−0.42, 0.41]	−0.01



Limits on C_{tZ}, $C_{t\gamma}$ for combination of $t\bar{t}\gamma$ and $t\bar{t}Z$

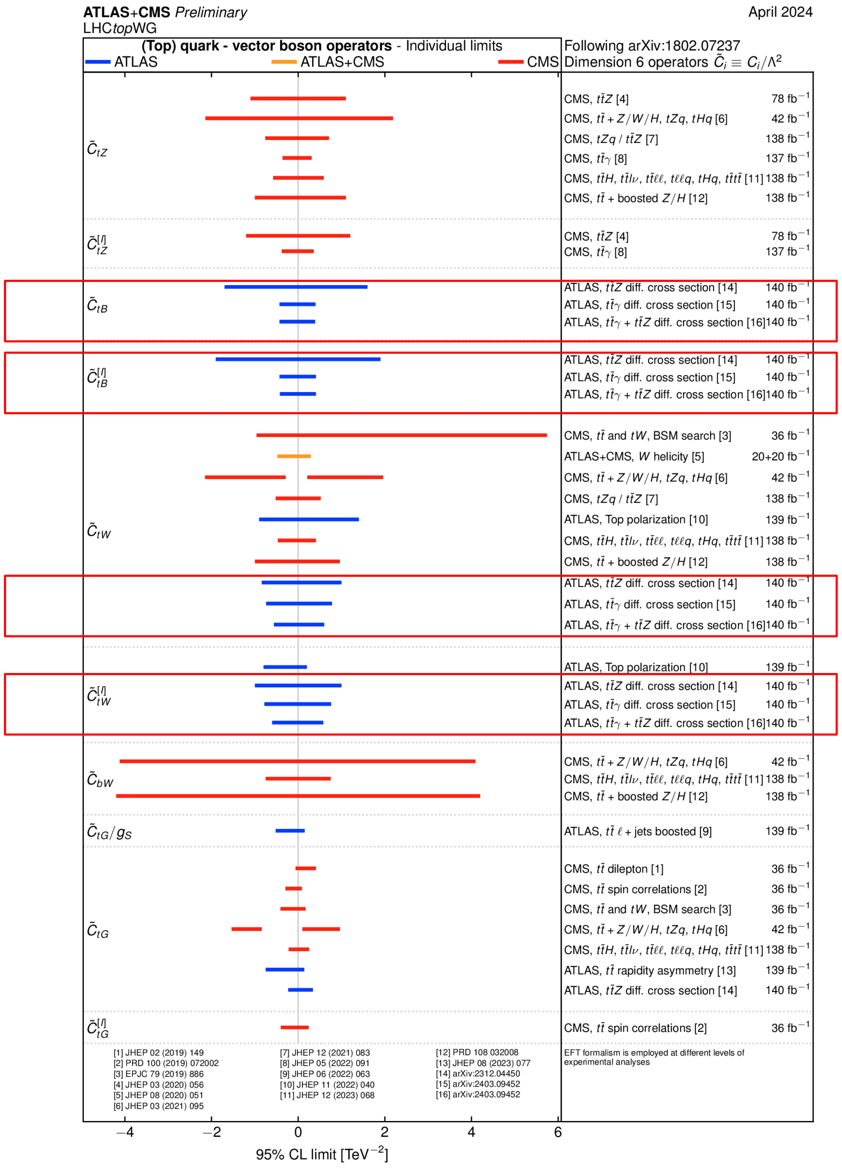


$$C_{tZ} = \cos(\Theta_W) \cdot C_{tW} - \sin(\Theta_W) \cdot C_{tB}$$
$$C_{t\gamma} = \sin(\Theta_W) \cdot C_{tW} + \cos(\Theta_W) \cdot C_{tB}$$

- These coefficients describe modifications of tγ and tZ vertex
- Results in agreement with Standard Model

Summary

- Inclusive and differential cross-section measurements in the single-lepton and dilepton channel measured in a fiducial phase space at particle level
  - Measured $t\bar{t}\gamma$ production only and $t\bar{t}\gamma$ total (regardless of photon origin)
  - General good agreement with predictions, absolute cross-sections slightly larger than predicted
- EFT interpretation of photon p_T and combination of photon p_T and Z p_T from $t\bar{t}Z$ (arXiv:2312.04450)
  - Results obtained in (C_{tB}, C_{tW}) basis, as well as ($C_{t\gamma}$, C_{tZ}) and (C_{tZ}, C_{tW}) basis
  - Results in agreement with SM assumption



Backup

Event selection

Single-lepton channel

- 1 photon, pT>20GeV, |η|<1.37 or 1.52<|η|<2.37
- 1 lepton p_T>25GeV
    - e: |η|<1.37 or 1.52<|η|<2.47
    - μ: |η|<2.5
- Anti k_T R=0.4 jets, N_{Jets}≥4, p_T>25GeV, |η|<2.5
- b-tagging: $N_{b\text{-}jets}$≥1 (DL1r tagged at 70%)
- |m(e,γ)-91.19GeV|>5GeV

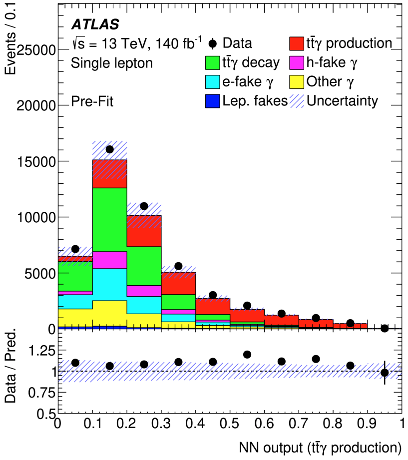
Dilepton channel

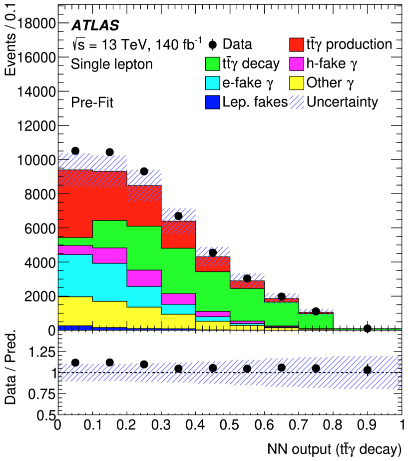
- 1 photon, pT>20GeV, |η|<1.37 or 1.52<|η|<2.37
- 2 lepton p_T>25GeV (leading) and p_T>20GeV (subleading)
- e: |η|<1.37 or 1.52<|η|<2.47
- μ: |η|<2.5
- Anti k_T R=0.4 jets, N_{Jets}≥2, p_T>25GeV, |η|<2.5
- b-tagging: $N_{b\text{-}jets}$≥1 (DL1r tagged at 85%)
- |m(l,l)-91.19GeV|>5GeV
- m(l,l)>15GeV
- MET>30GeV

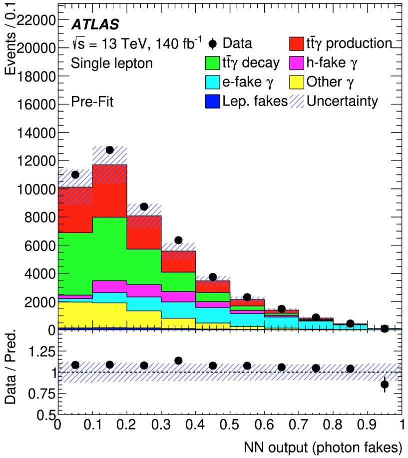
NN inputs

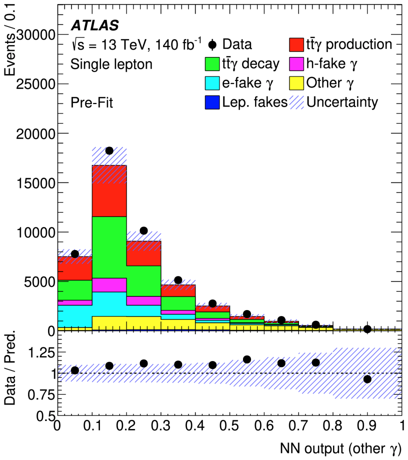
Single lepton	Dilepton
Invariant mass of photon and lepton	ΔR between photon and closest lepton
Photon p_{T}	Invariant mass of photon and closest lepton
ΔR of photon and lepton	Photon p_{T}
Invariant mass of photon and leading PCBT b-jet	Invariant mass of photon and closest b-jet
Sum of invariant masses of the reconstructed top quark and antitop quark (4 variables)	Photon energy
Photon energy	Scalar sum of p_T of all jets
Sum of squared differences between the top-quark pole mass and reconstructed $t\bar{t}$ mass (4 variables)	p_{T} and energy of the two jets with highest p_{T} (4 variables)
Invariant mass of all jets, the lepton and the photon	ΔR of photon and closest b-jet
H_T	$E_{\mathrm{T}}^{\mathrm{miss}}$
Reconstructed leptonic W boson p_{T}	Number of jets
p_{T} and energy of four jets with highest p_{T} (8 variables)	Photon η
ΔR between photon and closest b-jet	Number of b-jets
$E_{\mathrm{T}}^{\mathrm{miss}}$	Photon ϕ
Invariant mass of lepton and closest b-jet	
Number of jets	
Transverse mass of leptonic W boson	
ΔR between lepton and closest b-jet	
Invariant mass of reconstructed W bosons, shifted by the W boson (2 variables)	
Photon η	
PCBT distributions of the four jets with the highest scores (4 variables)	
Photon conversion type	
Number of b-jets	
Photon ϕ	

NN outputs

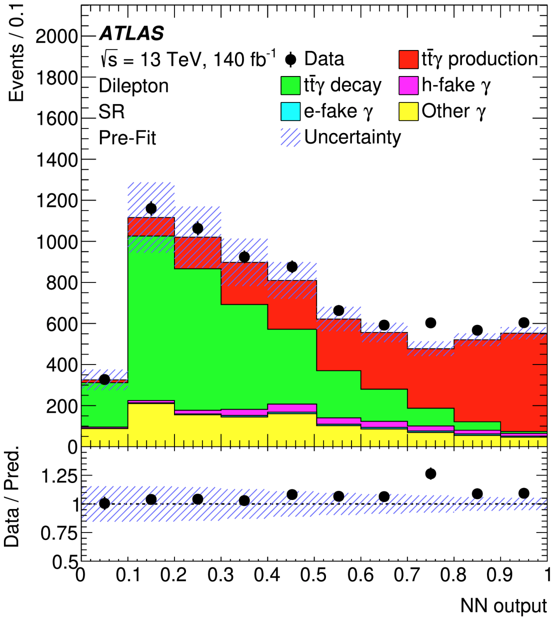






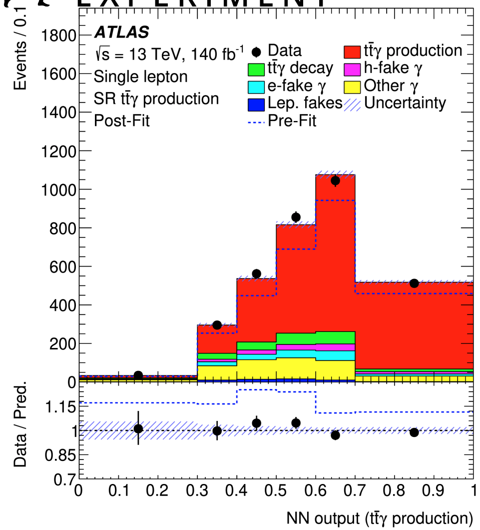


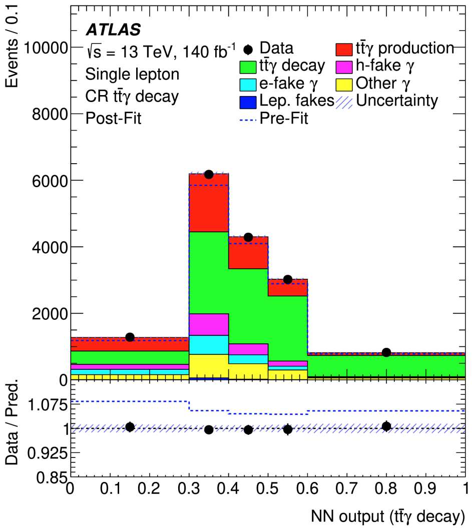
- Left side: The four output classifiers of the NN for single lepton channel
- Right side: Output of binary classifier for dilepton channel

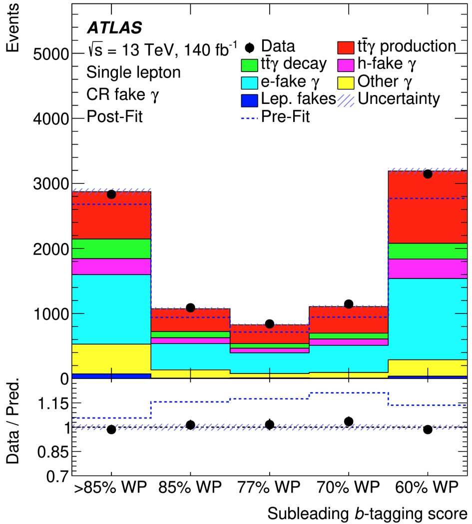


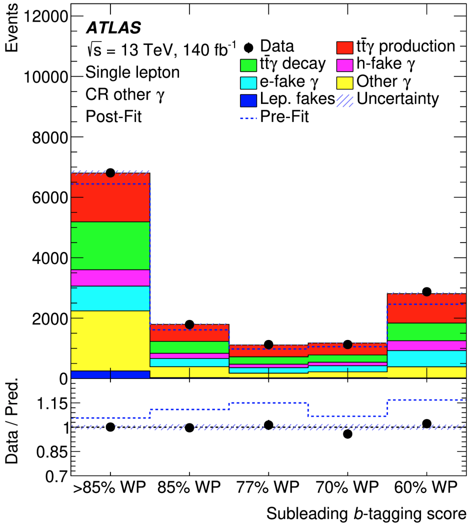
Category	$t\bar{t}\gamma$ decay classifier	fake γ classifier	other prompt γ classifier	purity
SR $t\bar{t}\gamma$ production	< 0.15	< 0.2	< 0.5	73%
CR $t\bar{t}\gamma$ decay	> 0.25	–	< 0.4	71%
CR fake γ	< 0.15	> 0.2	< 0.5	50%
CR Other γ		remaining events		26%

Post-fit distributions input variables



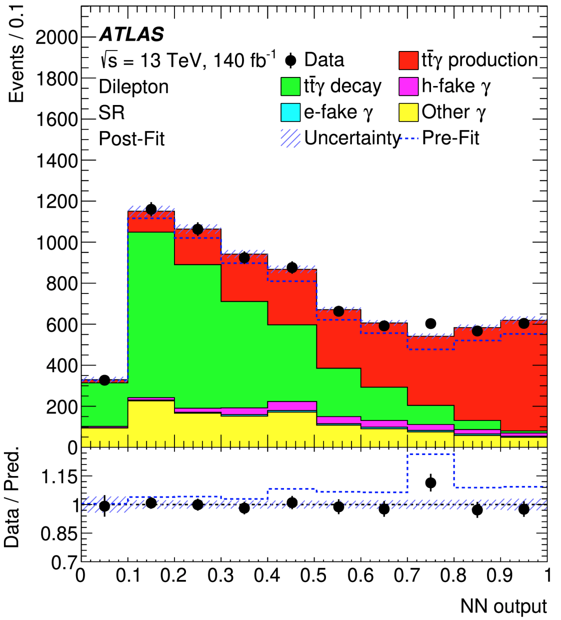






Sown are the input variables for the inclusive cross-section

Input variables in the SR and 3 CRs in the single-lepton channel



NN output dilepton channel

Inclusive cross-section: total $t\bar{t}\gamma$

	Fiducial cross section (fb)
Combined	793±5(stat)±38(syst)
Single lepton	707±6(stat)±48(syst)
Dilepton	117.7±1.7(stat)±7.9(syst)

- Combination obtained (like for $t\bar{t}\gamma$ production) from simultaneous likelihood fit to all SRs and CRs
- $t\bar{t}\gamma$ cross section: precision around 7.7% per channel, 5.2% from combination
- Similar precision as $t\bar{t}\gamma$ production (slightly smaller statistical uncertainty, slightly larger uncertainty on $t\bar{t}\gamma$ decay, no differences between experimental uncertainties as expected)

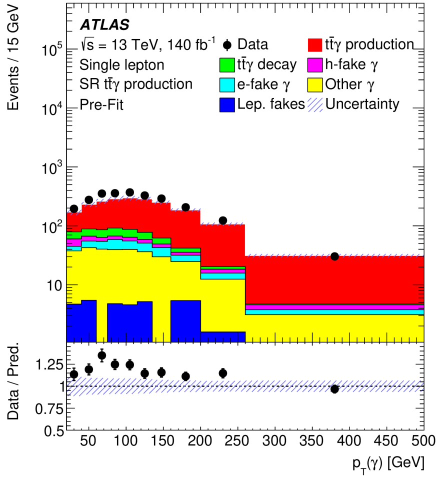
χ^2 and p-values in production

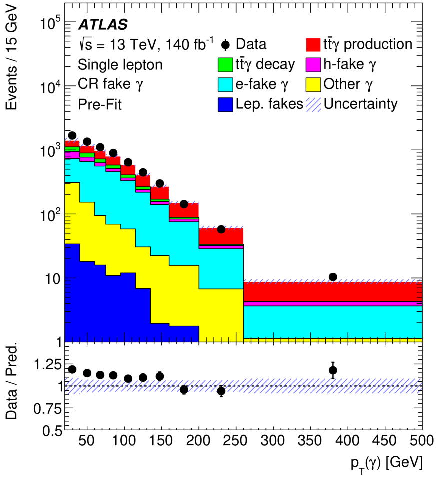
Variables	Absolute cross-sections: MG5_aMC@NLO+Pythia 8 χ^2/ndf	Absolute cross-sections: MG5_aMC@NLO+Pythia 8 p-value	Absolute cross-sections: MG5_aMC@NLO+Herwig 7 χ^2/ndf	Absolute cross-sections: MG5_aMC@NLO+Herwig 7 p-value	Normalised cross-sections: MG5_aMC@NLO+Pythia 8 χ^2/ndf	Normalised cross-sections: MG5_aMC@NLO+Pythia 8 p-value	Normalised cross-sections: MG5_aMC@NLO+Herwig 7 χ^2/ndf	Normalised cross-sections: MG5_aMC@NLO+Herwig 7 p-value
Single-lepton and dilepton combined								
$p_T(\gamma)$	10.1/10	0.44	9.0/10	0.54	15.0/9	0.09	10.4/9	0.32
$\|\eta(\gamma)\|$	14.6/8	0.07	13.5/8	0.09	10.4/7	0.17	10.5/7	0.16
Single-lepton channel								
$p_T(\gamma)$	12.3/10	0.26	11.1/10	0.35	64.8/9	< 0.01	49.6/9	< 0.01
$\|\eta(\gamma)\|$	11.5/8	0.18	11.0/8	0.20	8.0/7	0.33	8.3/7	0.31
$\Delta R(\gamma, \ell)$	10.2/7	0.18	9.6/7	0.22	8.5/6	0.20	8.5/6	0.21
$\Delta R(\gamma, b)_{min}$	12.4/5	0.03	12.0/5	0.04	7.5/4	0.11	8.7/4	0.07
$\Delta R(\ell, j)_{min}$	6.1/5	0.30	6.4/5	0.27	1.5/4	0.83	2.5/4	0.64
$p_T(j_1)$	12.0/5	0.04	10.5/5	0.06	8.1/4	0.09	9.7/4	0.05
Dilepton channel								
$p_T(\gamma)$	8.4/6	0.21	7.0/6	0.32	6.3/5	0.28	5.3/5	0.38
$\|\eta(\gamma)\|$	12.2/8	0.14	9.9/8	0.27	9.2/7	0.24	7.8/7	0.35
$\Delta R(\gamma, \ell)_{min}$	17.6/7	0.01	17.2/7	0.02	14.2/6	0.03	14.7/6	0.02
$\Delta R(\gamma, b)_{min}$	7.7/5	0.17	5.0/5	0.41	1.4/4	0.84	0.8/4	0.93
$\Delta R(\ell, j)_{min}$	13.6/5	0.02	9.7/5	0.08	5.3/4	0.26	3.7/4	0.44
$p_T(j_1)$	10.2/5	0.07	4.9/5	0.42	7.8/4	0.10	3.6/4	0.46

χ^2 and p-values in production+decay

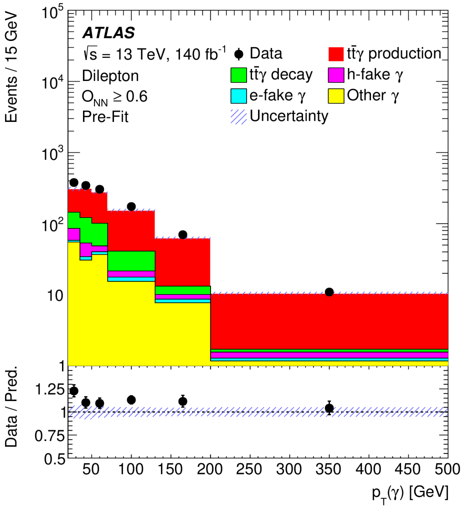
Variables	Absolute cross-sections				Normalised cross-sections			
	MG5_aMC@NLO+PYTHIA 8		MG5_aMC@NLO+HERWIG 7		MG5_aMC@NLO+PYTHIA 8		MG5_aMC@NLO+HERWIG 7	
	χ^2/ndf	p-value	χ^2/ndf	p-value	χ^2/ndf	p-value	χ^2/ndf	p-value
Single-lepton channel								
$p_T(\gamma)$	12.9/10	0.23	8.7/10	0.56	122.4/9	< 0.01	31.6/9	< 0.01
$\lvert\eta(\gamma)\rvert$	13.3/8	0.10	13.3/8	0.10	12.2/7	0.09	13.1/7	0.07
$\Delta R(\gamma, \ell)$	15.2/7	0.03	14.2/7	0.05	18.5/6	0.01	17.3/6	0.01
$\Delta R(\gamma, b)_{\text{min}}$	8.6/5	0.12	5.9/5	0.31	9.1/4	0.06	5.8/4	0.21
$\Delta R(\ell, j)_{\text{min}}$	4.7/5	0.46	2.9/5	0.71	0.8/4	0.93	0.9/4	0.93
$p_T(j_1)$	25.2/5	< 0.01	43.5/5	< 0.01	27.8/4	< 0.01	45.2/4	< 0.01
Dilepton channel								
$p_T(\gamma)$	7.5/6	0.28	4.3/6	0.64	6.4/5	0.27	4.1/5	0.53
$\lvert\eta(\gamma)\rvert$	5.3/8	0.73	6.5/8	0.59	5.5/7	0.60	6.8/7	0.45
$\Delta R(\gamma, \ell)_{\text{min}}$	24.7/7	< 0.01	24.3/7	< 0.01	21.0/6	< 0.01	20.7/6	< 0.01
$\Delta R(\gamma, \ell_1)$	9.1/7	0.25	7.7/7	0.36	9.0/6	0.17	7.5/6	0.28
$\Delta R(\gamma, \ell_2)$	17.1/7	0.02	18.1/7	0.01	16.7/6	0.01	17.7/6	0.01
$\lvert\Delta\eta(\ell, \ell)\rvert$	4.0/7	0.78	7.0/7	0.43	3.3/6	0.78	5.8/6	0.45
$\Delta\phi(\ell, \ell)$	35.8/8	< 0.01	37.6/8	< 0.01	35.6/7	< 0.01	37.3/7	< 0.01
$p_T(\ell, \ell)$	6.5/6	0.37	12.5/6	0.05	5.8/5	0.33	11.5/5	0.04
$\Delta R(\gamma, b)_{\text{min}}$	0.7/5	0.98	2.4/5	0.79	0.7/4	0.95	2.4/4	0.66
$\Delta R(\ell, j)_{\text{min}}$	6.1/5	0.3	8.9/5	0.11	9.9/4	0.04	12.4/4	0.01
$p_T(j_1)$	11.5/5	0.04	21.1/5	< 0.01	10.4/4	0.03	19.3/4	< 0.01

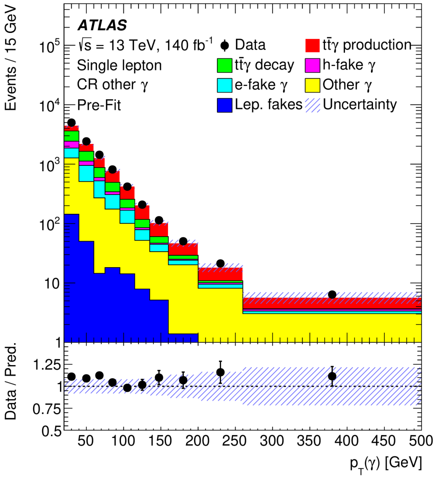
Photon pt distributions in SRs and CR

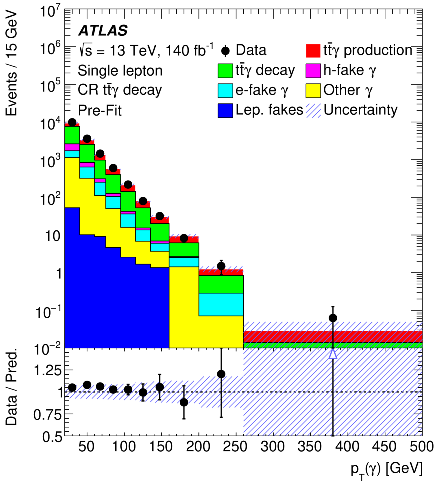


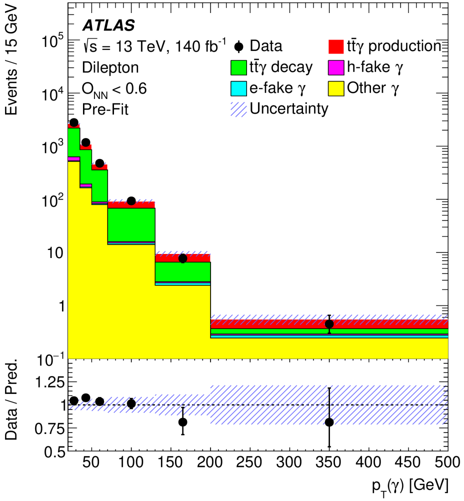


Shown are the inputs for the differential cross-section measurement



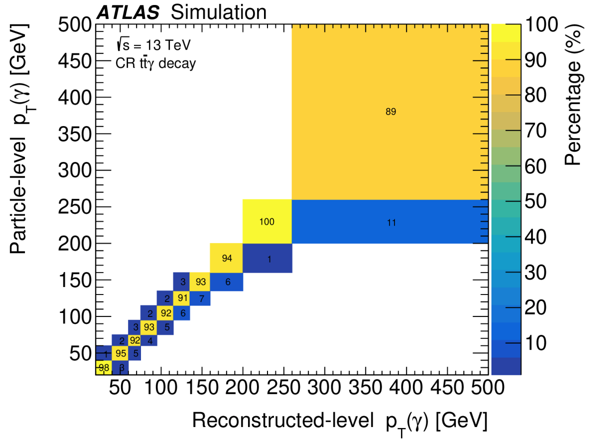


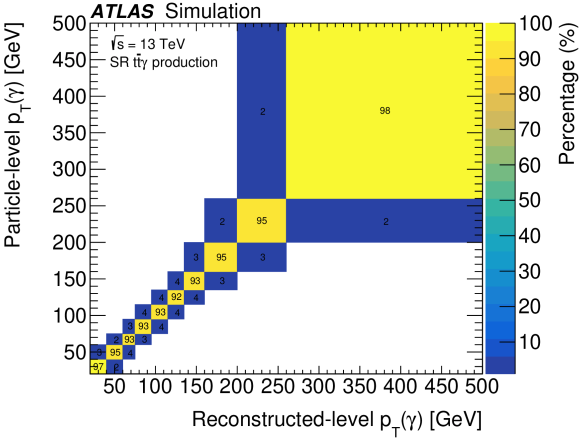


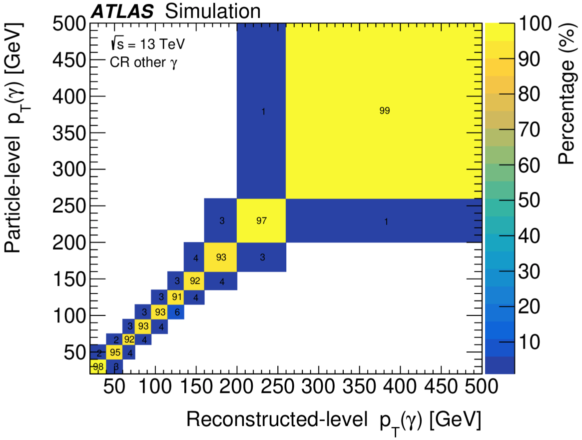


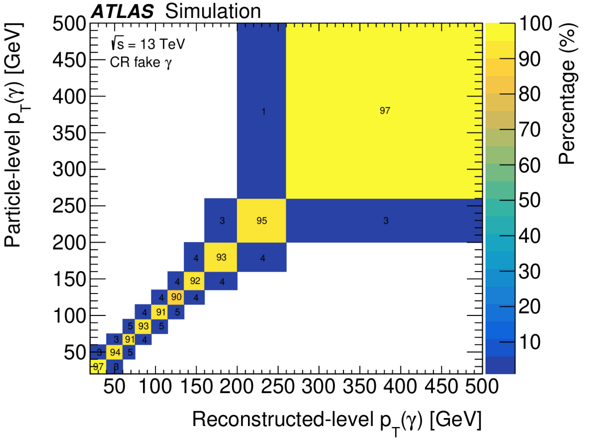
Migration matrix for single-lepton channel

- Migration between particle level and reconstruction level
- Little migration observed



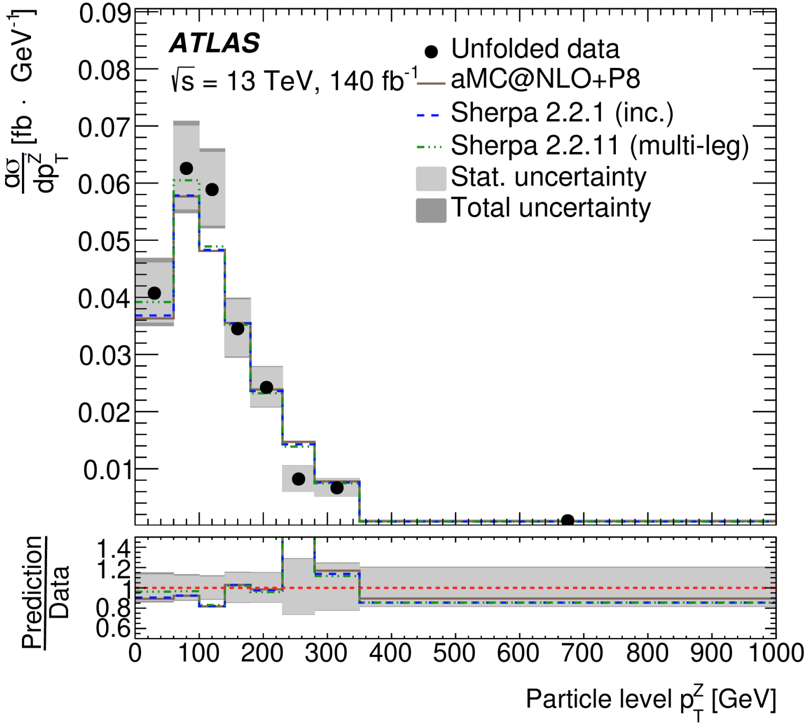




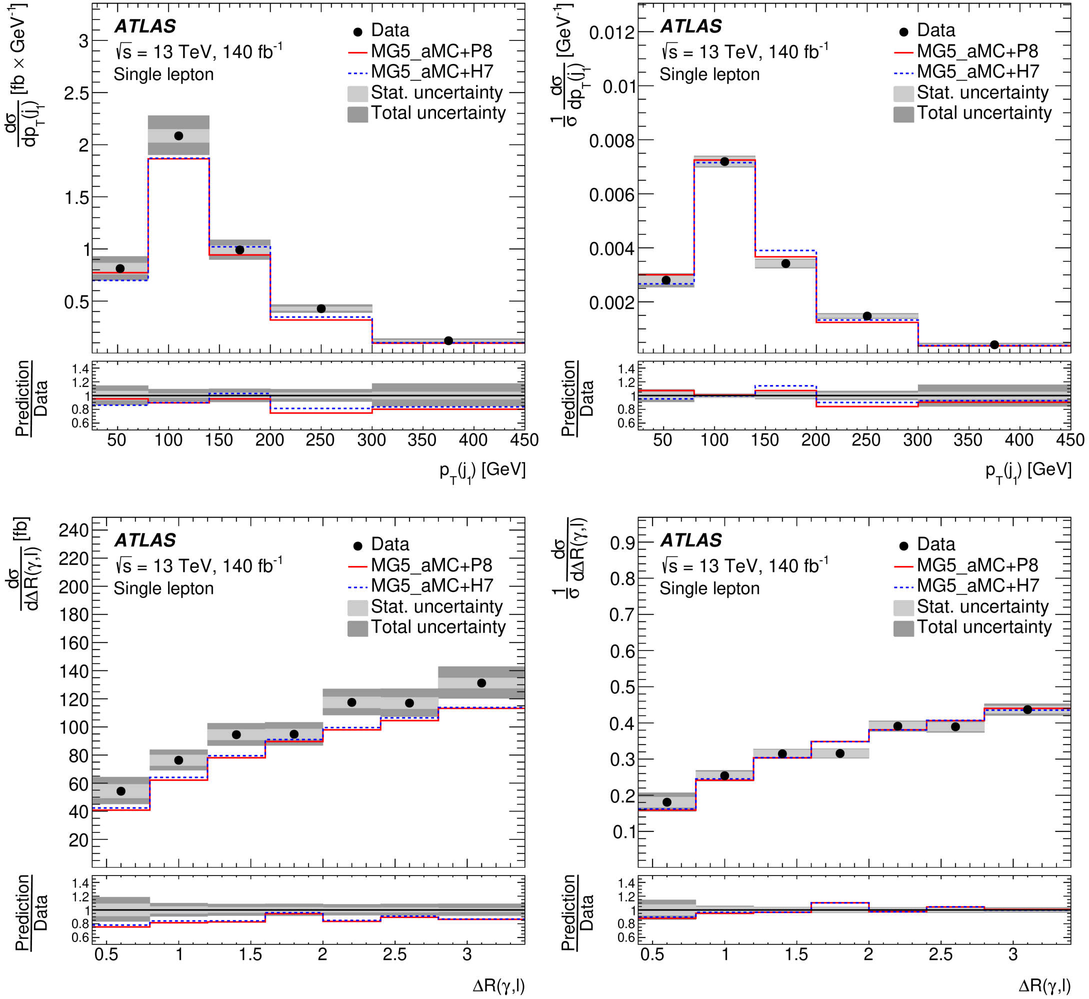


$t\bar{t}Z$ measurement

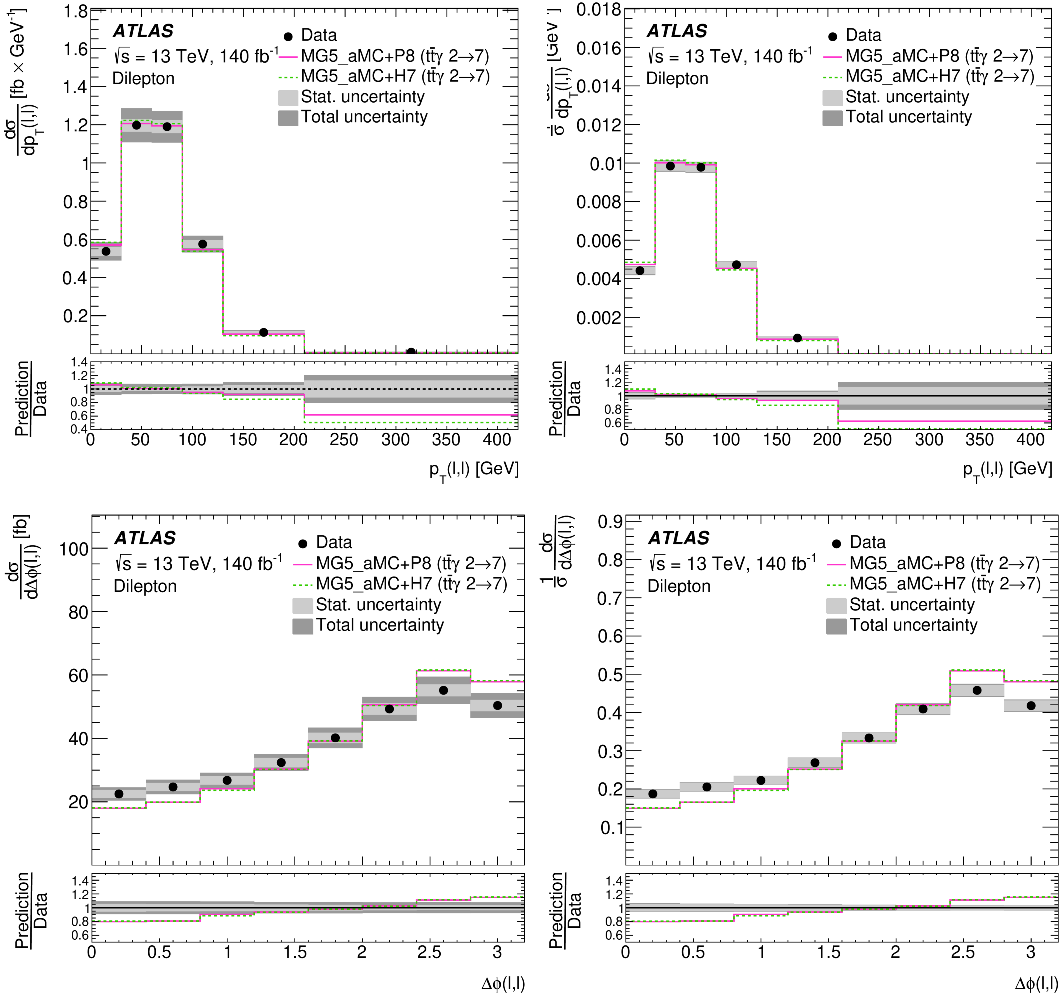
- Unfolded to fiducial phase space: p_T of the Z boson in combination trilepton and tetralepton final states
  - Phase space orthogonal to $t\bar{t}\gamma$
- Regions split further based on lepton flavour and charge
- NN based separation of signal and background
- Measured cross-section in good agreement with NLO MC prediction
- Statistical uncertainty dominant source of uncertainty



$t\bar{t}\gamma$ production: Single lepton channel

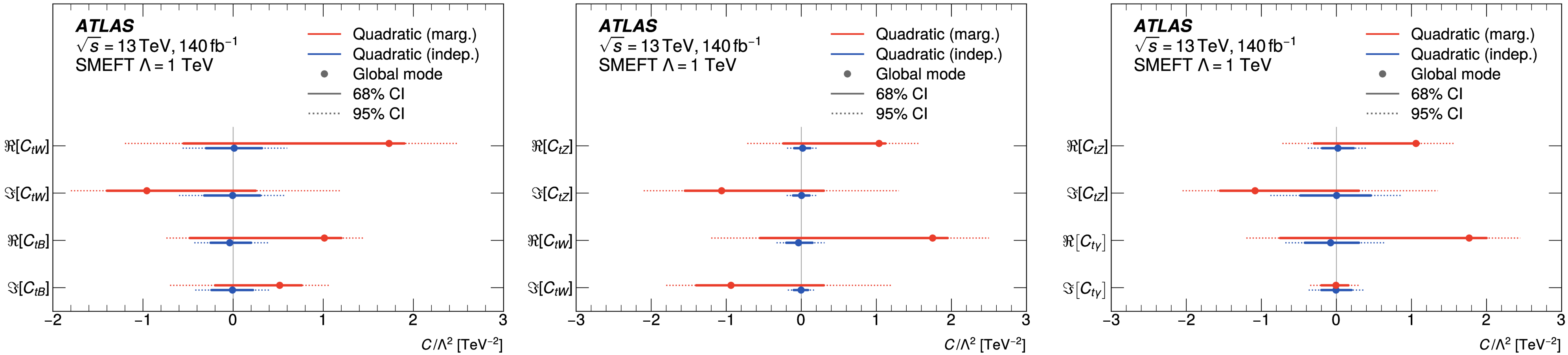


$t\bar{t}\gamma$ total: Dilepton channel

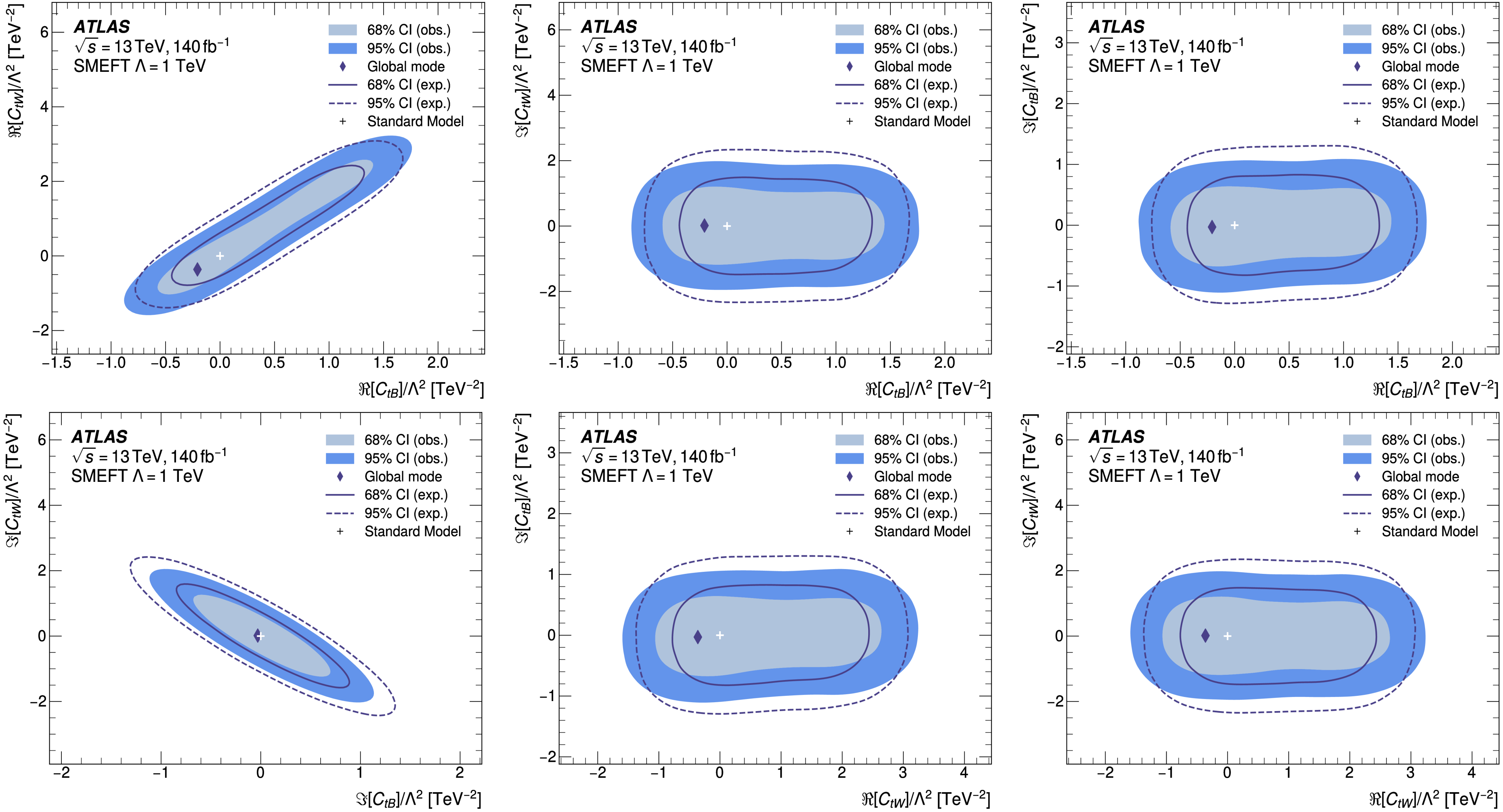


EFT limits (combination)

- The EFT limits in the three different operator bases investigated



Limits on C_{tB}, C_{tW} from $t\bar{t}\gamma$ production



Limits on C_{tZ} $C_{t\gamma}$ for combination of $t\bar{t}\gamma$ and $t\bar{t}Z$