Karlsruher Institut für Technologie

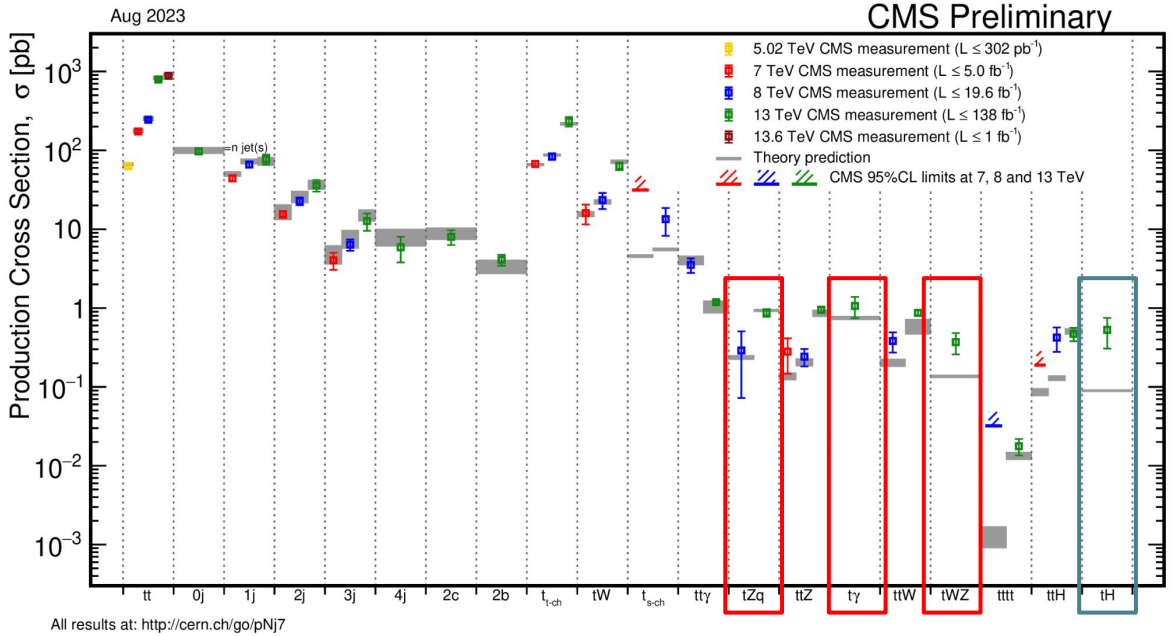
Associated single top production

Nils Faltermann on behalf of the ATLAS and CMS Collaborations

16th International Workshop on Top Quark Physics
September 24th - 29th, 2023

Associated single top quark production

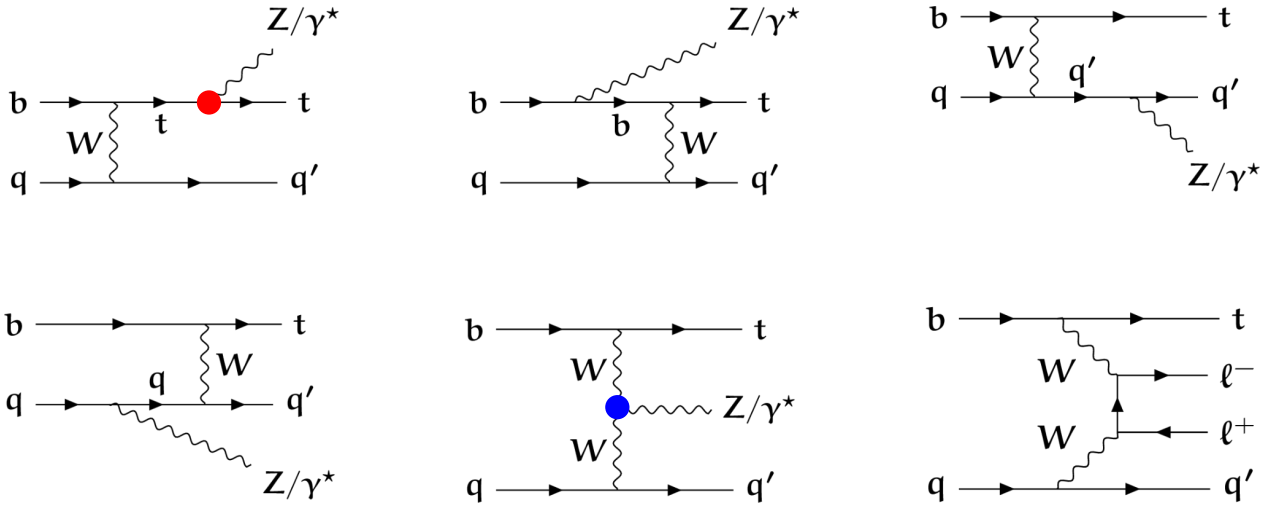
- Standard single top quark production modes **+ (neutral) vector boson**
- Very low production cross sections, **sub-pb**
- Production and decay via EW interaction



For tH, see talk by Lucia

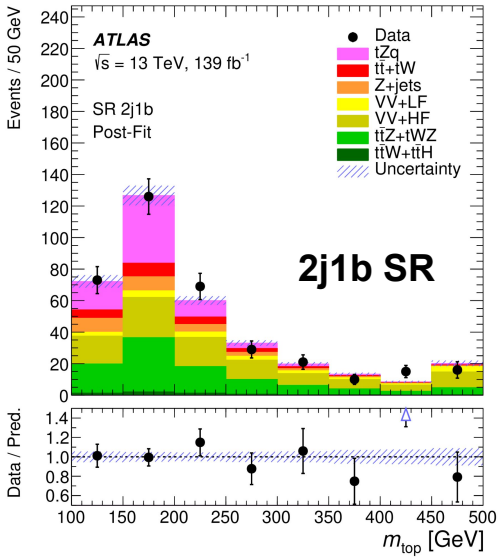
tZq - Overview

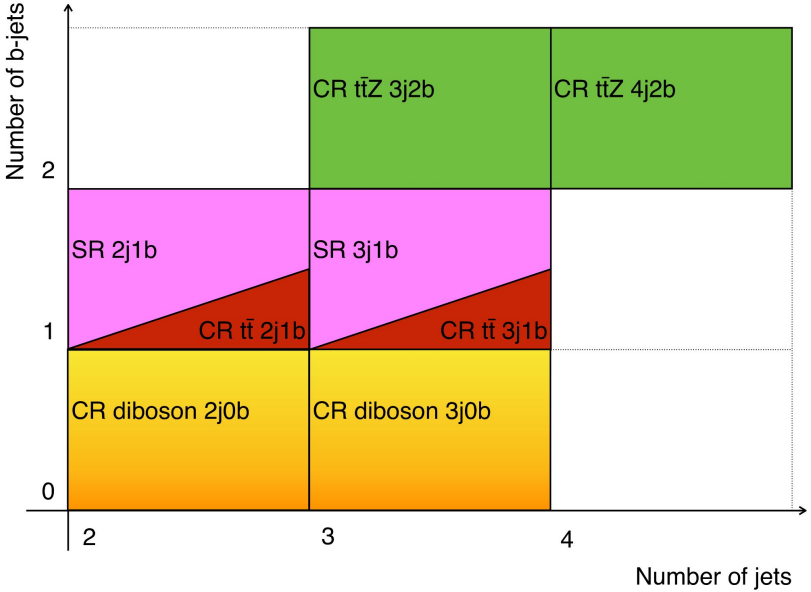
- ***t* channel** production mode (tq)
- Z boson can couple to any quark, but also to the W boson propagator
  - Probing both ttZ and WWZ coupling
- **Leptonic Z boson decays**
- Nonresonant background



tZq ATLAS - Measurement (139 fb^{-1}) JHEP 07 (2020) 124

- 3 leptons (e or μ)
  - 2 OSSF from Z boson
  - $|m_{ll} - m_Z| < 10$ GeV
  - 1 from leptonic top quark decay



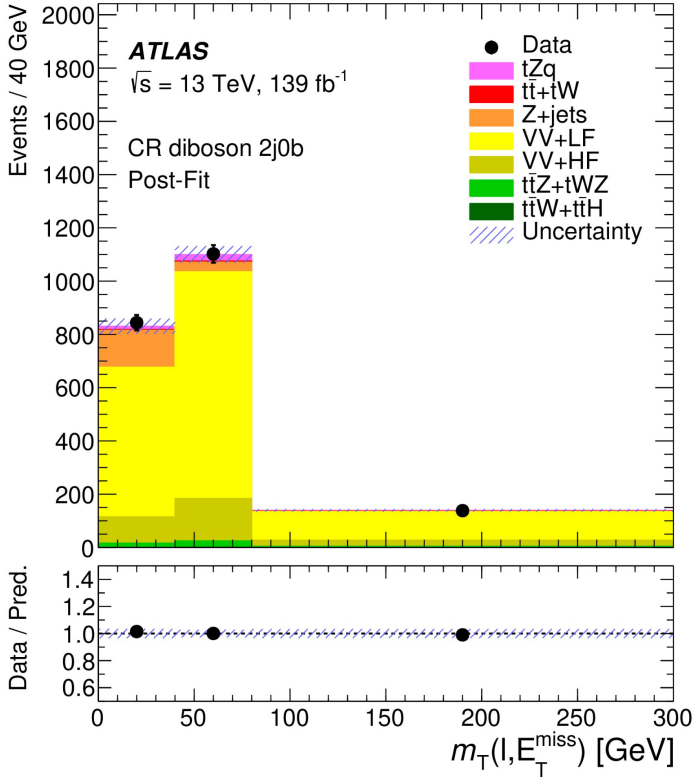


- Event categorization by **jet multiplicity** → SRs + CRs
- For tt CRs OSDF lepton pair

tZq ATLAS - Backgrounds

JHEP 07 (2020) 124

- Contributing backgrounds:
  - Prompt leptons from **VV, ttV, ttH**
  - Nonprompt leptons on top of **Z+jets, tt**
- **Prompt leptons** from dedicated CRs
  - Constrain normalization
  - Control systematic uncertainties
- **Nonprompt** modeling in MC validated with dedicated b jet study
  - Origin mostly semileptonic b and c hadron decays in tt/Z+jets
  - 2 lepton + 2 b jet selection, replacing random b jet with lepton



tZq ATLAS - Results

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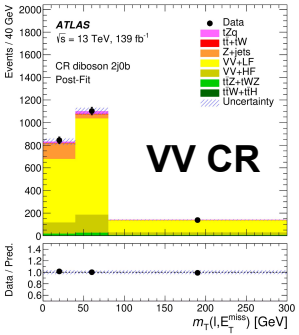
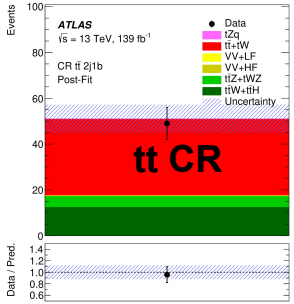
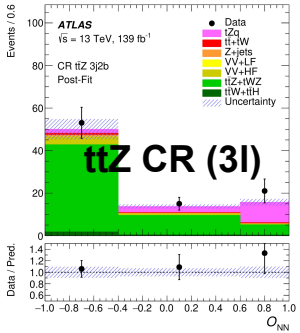
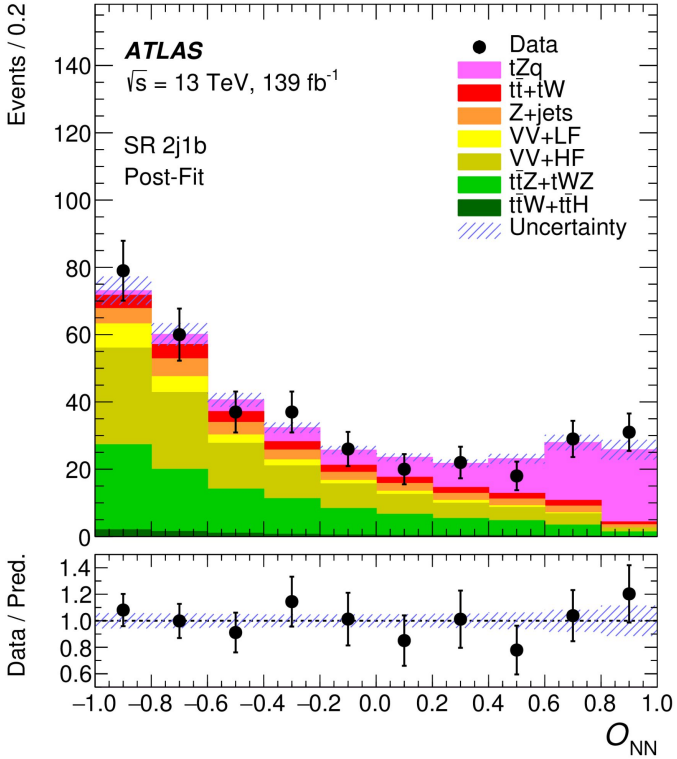
- NN to maximize sensitivity
- Simultaneous fit of all SRs and CRs
  - exp/obs significance **>5σ**
  - **σ_{tZq} = 97 ± 13 (stat) ± 7 (syst) fb**
- In agreement with prediction (m_{ll} > 30 GeV)
  - $\sigma_{tZq,SM} = 102^{+5}_{-2}$ fb (aMC@NLO)
- Prompt leptons dominant syst uncertainty







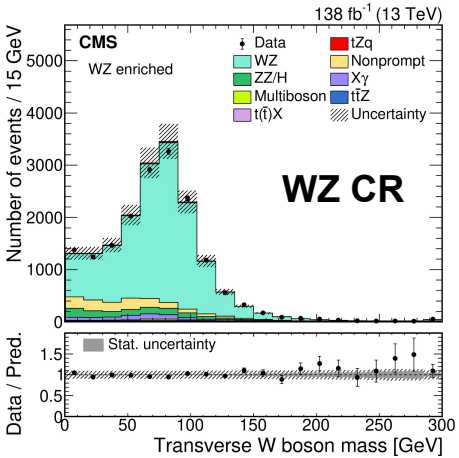


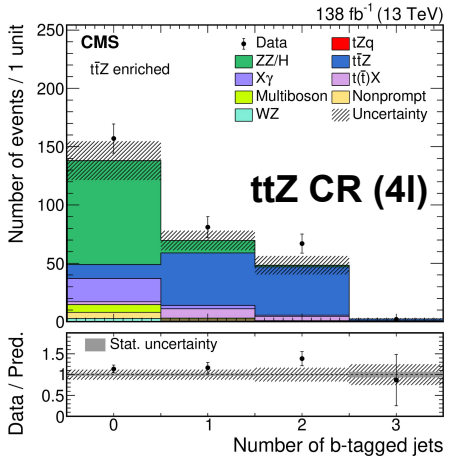
tZq CMS - Measurement (138 fb^{-1})

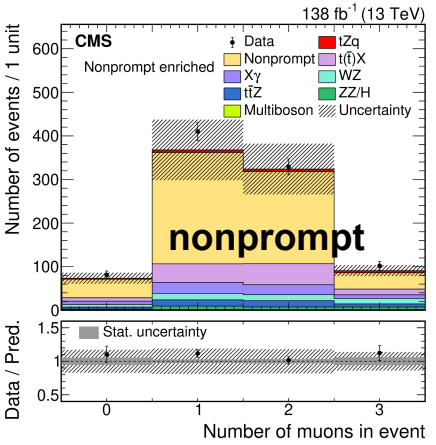
JHEP 02 (2022) 107

- 3 leptons (e or μ), 2 OSSF
- Different jet categories for SRs:
  - 1 b jet, 2 or 3 jets
  - 1 b jet, ≥4 jets
  - ≥2 b jets

- Dedicated CRs for prompt lepton background
- Nonprompt from data in sideband via **transfer function** of p_T and η







tZq CMS - Inclusive results

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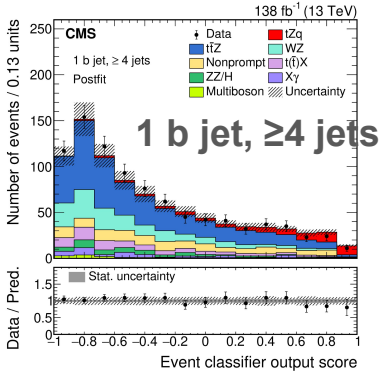
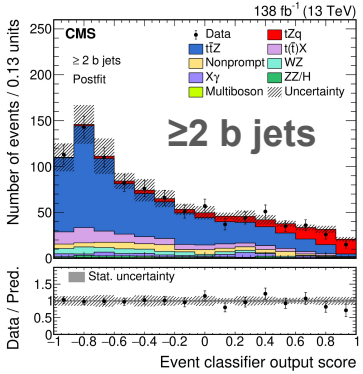
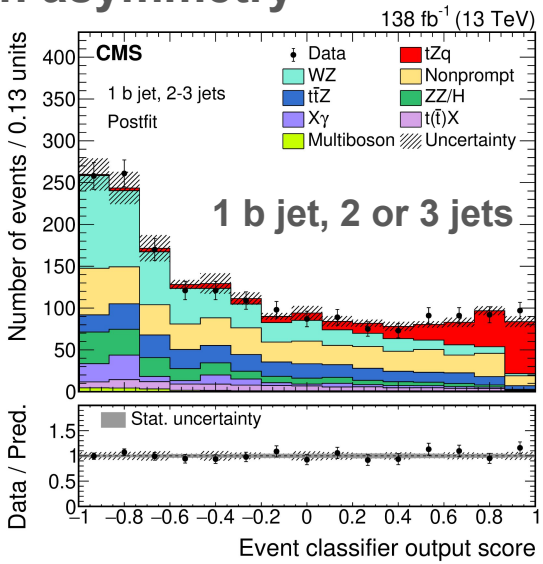
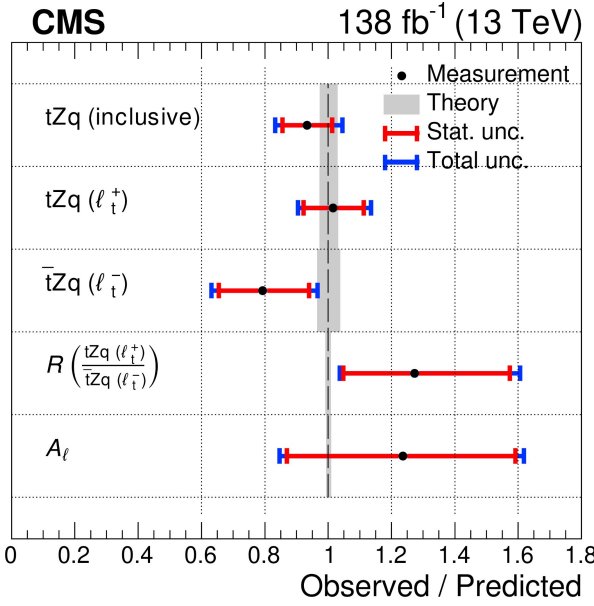
- Combined fit to BDT output in SRs and CRs
  - $\sigma_{tZq} = 87.9^{+7.5}_{-7.3}\,(stat)\,^{+7.3}_{-6.0}\,(syst)$ fb ($\sigma_{tZq,SM} = 94.2^{+1.9}_{-1.8}$ (scale) ± 2.5 (PDF) fb (aMC@NLO))
- Dominating syst uncertainty tZq scale, nonprompt
- Precision measurement → differential cross section e.g. of cos(θ*) to extract **spin asymmetry**









tZq CMS - Differential results

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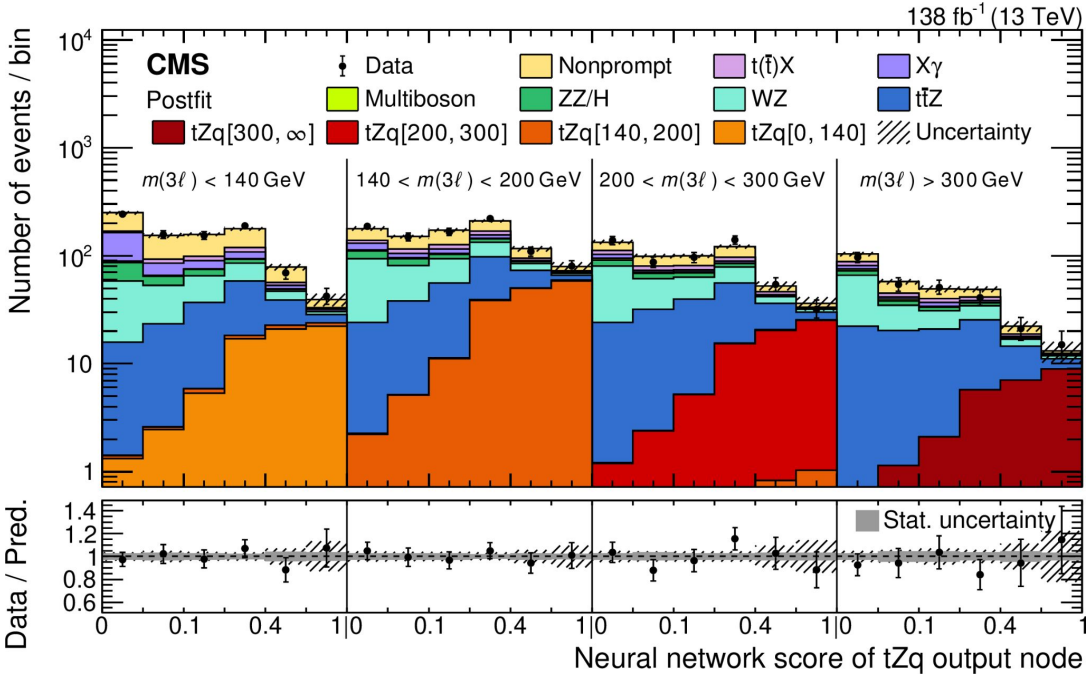
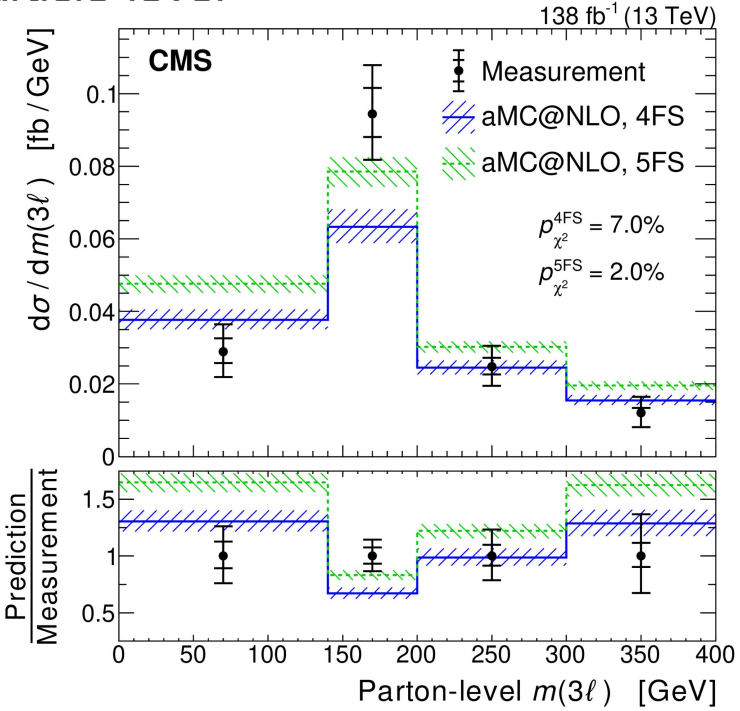
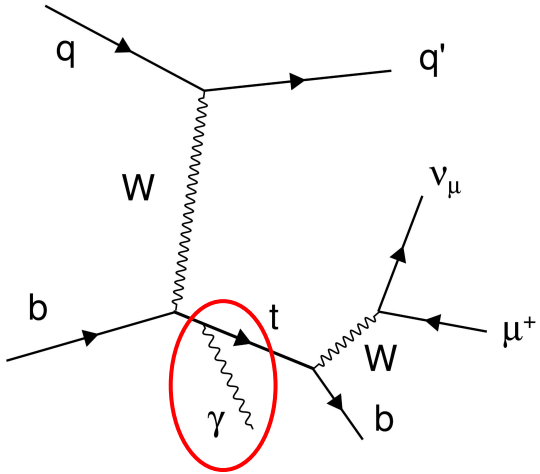
- Classification with a DNN, CRs tighter defined
- Likelihood-based unfolding to parton- and particle-level

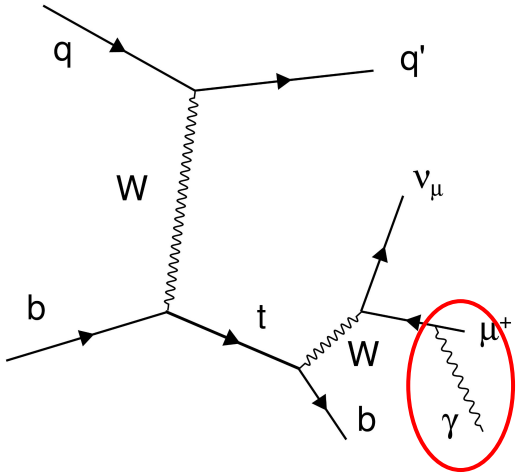


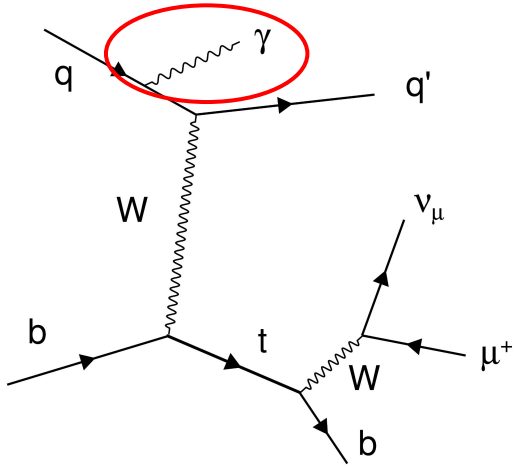


tqɣ - Overview

- Very rare process in the SM
- ***t* channel** production mode
- Sensitive to top quark charge, electric and magnetic dipole moments
- ɣ from top quark or its decay products?



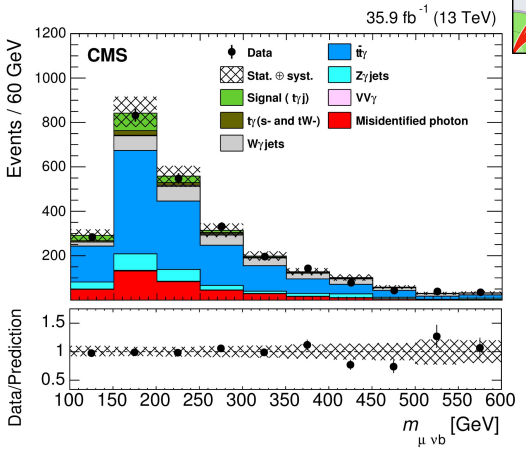


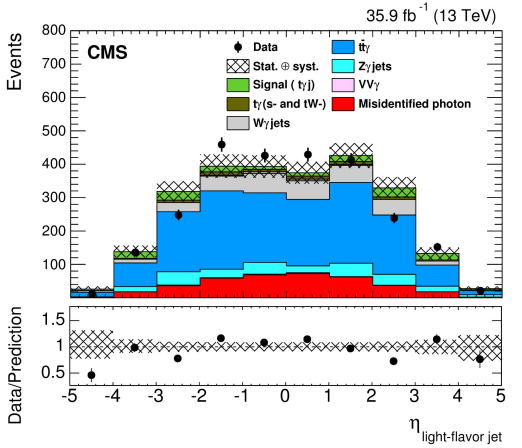


tqγ CMS - Measurement (35.9 fb^{-1})

PRL 121 (2018) 221802

- 2016 data only
- SR selection: **1 μ, 1 γ, p_T^{miss} > 30 GeV, ≥2 jets, 1 b jet**
- CR with 2 b jets for data-driven ttγ shape
- Remaining prompt photon background (Wγ, Zγ) from simulation
- **Fake photon** (e → γ or h → γ) background (tt, W, Z) estimated from data
  - ABCD method: γ shower shape & isolation
  - Shape from CR enriched in nonprompt photons

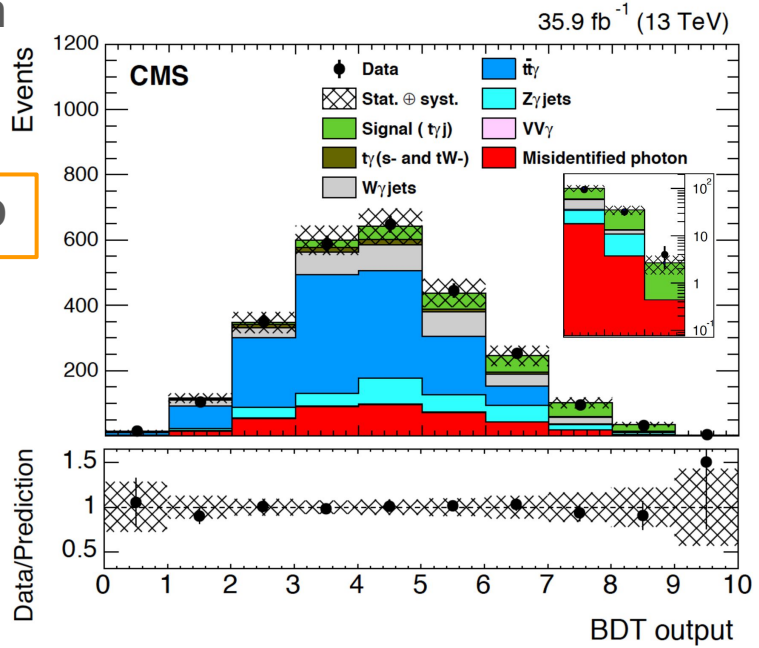




tqγ CMS - Results

PRL 121 (2018) 221802

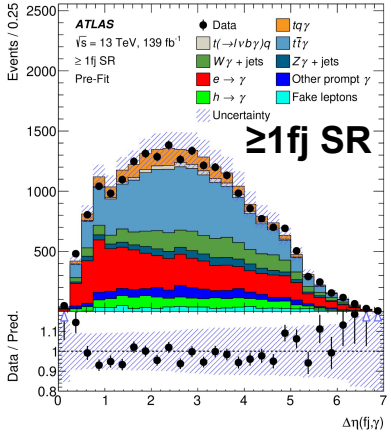
- BDT to maximize sensitivity
- Simultaneous fit of SR and CR, ttγ contribution unconstrained
- **4.4σ observed** (3.0σ expected) significance
- **$\sigma_{tq\gamma}$*B(t→μνb) = 115 ± 17 (stat) ± 30 (syst) fb** for fid. selection: $p_{T,\gamma} > 25$ GeV, $|\eta_\gamma| < 1.44$, $\Delta R(X, \gamma) > 0.5$
- SM pred. $\sigma_{tq\gamma,SM}$*B(t→μνb) = 81 ± 4 fb
- Dominant syst unc.: JES, signal modelling

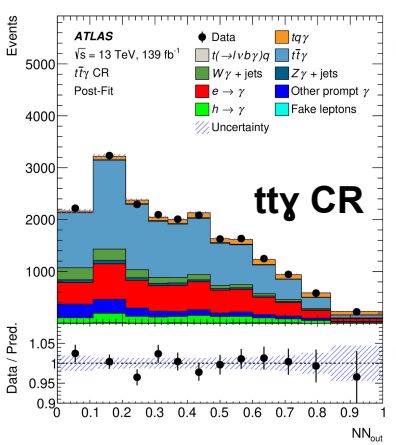


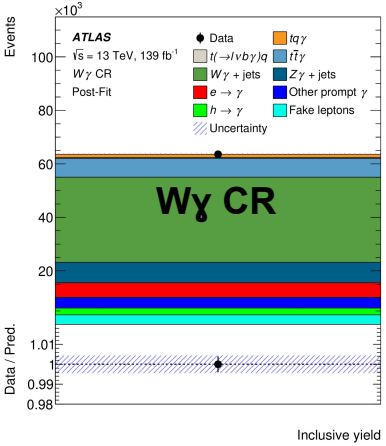
tqγ ATLAS - Measurement (139 fb^{-1})

arXiv:2302.01283
Accepted by PRL

- **1 e or μ, 1 γ, E_T^{miss} > 30 GeV, 1 b jet**
- SRs require either 0 or ≥1 **forward jets**
- $|m_{e\gamma}$ - 90 GeV| > 10 GeV to suppress Z → ee
- Backgrounds:
  - **ttγ** and **Wγ** constrained via CR in the fit
  - **e → γ** (dileptonic tt, Z): ee/eγ around Z peak, fake prob. for MC from data vs. MC
  - **h → γ** (semileptonic tt): ABCD method: γ ID & isolation



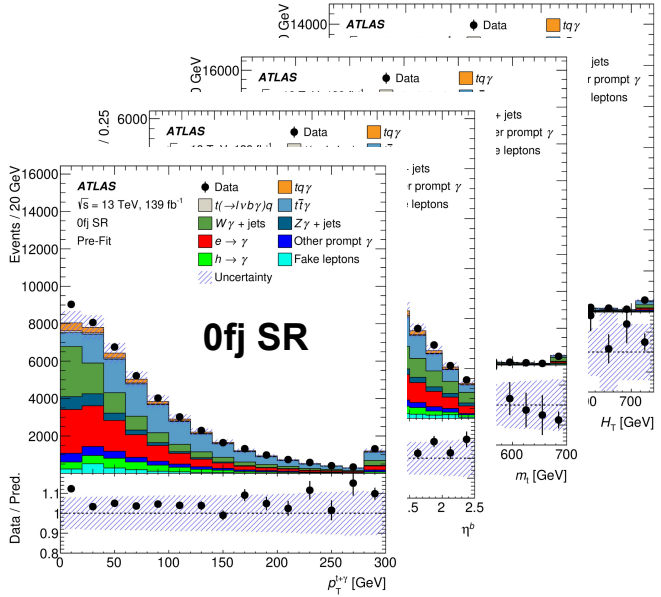


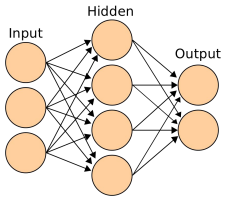


tqγ ATLAS - Signal extraction

arXiv:2302.01283
Accepted by PRL

- **Separate NNs** trained for each SR
- Kinematic features of γ, lepton, b jet, forward jet:
  - p_T, η, φ, m/E
  - Angular separation between objects
- Simultaneous fit in SRs and CRs
  - NN output in SRs
  - NN output for ttγ CR, depending on forward jet
  - Yield for Wγ CR

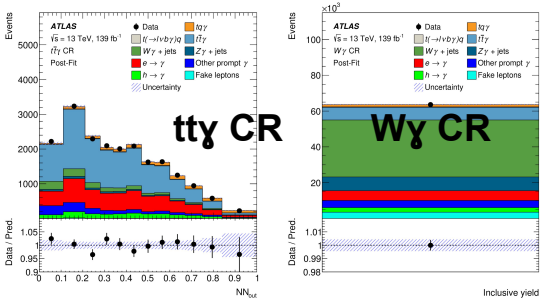


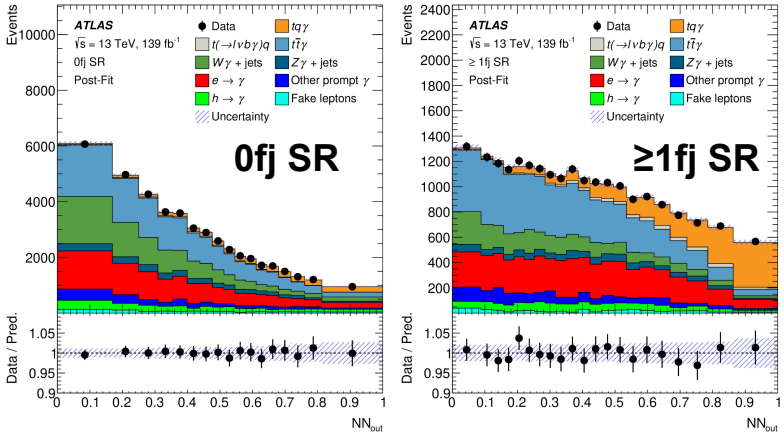


tqγ ATLAS - Results

arXiv:2302.01283
Accepted by PRL

- Significance **9.1σ** (6.7σ) → **first observation**
- Parton-level cross section:
  - $\sigma_{tq\gamma}$*B(t→lνb) = 688 ± 23 (stat) $^{+75}_{-71}$ (syst) fb
  - Fid. selection: $p_{T,\gamma} > 20$ GeV, $|\eta_\gamma| < 2.37$, $\Delta R_{Frixione} = 0.2$
  - Pred. (NLO QCD): 515^{+36}_{-42} fb (comp. 2.1σ)
- Particle-level cross section:
  - $\sigma_{tq\gamma}$*B(t→lνb) + $\sigma_{t(\gamma l\nu b)q}$ = 303 ± 9 (stat) $^{+33}_{-32}$ (syst) fb
  - Fid. selection: $p_{T,\gamma} > 20$ GeV, $|\eta_\gamma| < 2.37$, $\Delta R(X, \gamma) > 0.4$, lepton and jet p_T+η
  - Pred. (NLO QCD): 217^{+27}_{-15} fb (comp. 2.0σ)
- Dominant syst. unc.: ttγ modelling, background MC stats.

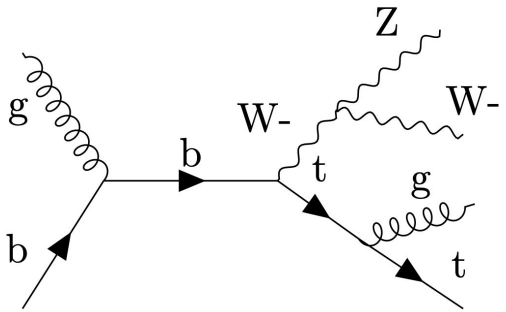




tWZ CMS - Measurement (138 fb^{-1})

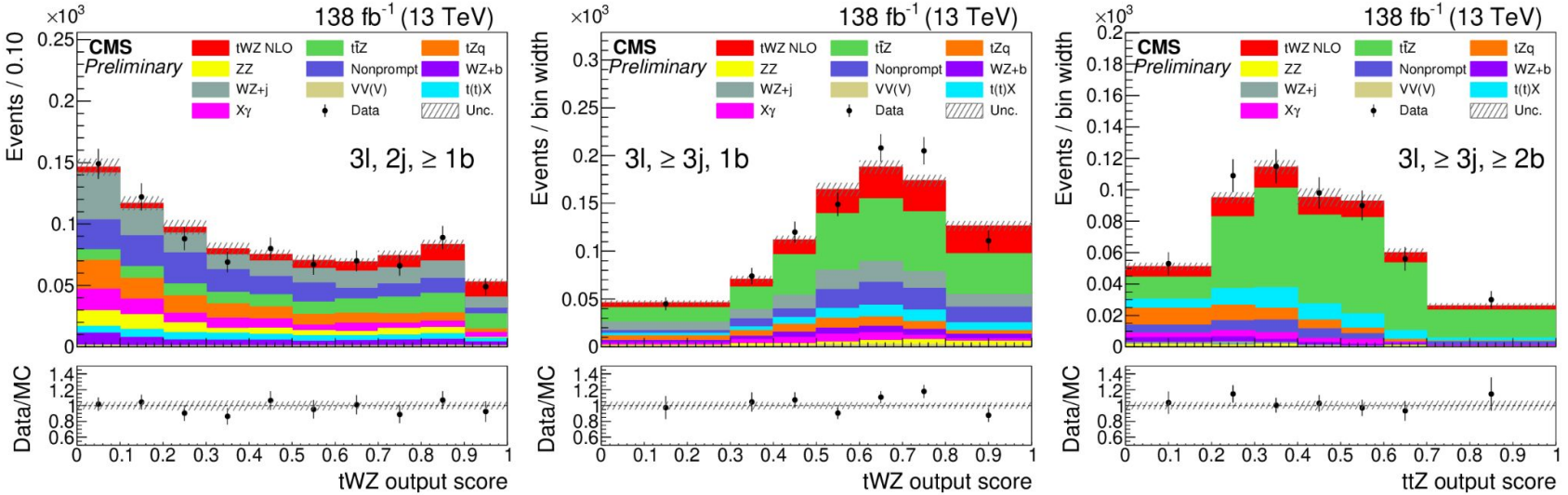
CMS-PAS-TOP-22-008

- Single top **tW production** + Z boson
- Targeting **different decay mode combinations**
  - Combined t+W+Z decay: ≥3 leptons, ≥2 jets, ≥1 b jet
  - Boosted category targeting high-p_T regime
  - CRs for diboson background
- Signal extraction:
  - SR_{3l2j}: **Binary classification DNN**: tWZ vs. backgrounds
  - SR_{3l3j}: **Multiclassification DNN**: tWZ vs. ttZ vs. other backgrounds
    - **tWZ node** for events with 1 b jet
    - **ttZ node** for events with ≥2 b jets
  - SR_{4l}: b jet multiplicity
  - $SR_{Boosted}$, CR_{ZZ}, CR_{WZ}: Event yield



tWZ CMS - Results

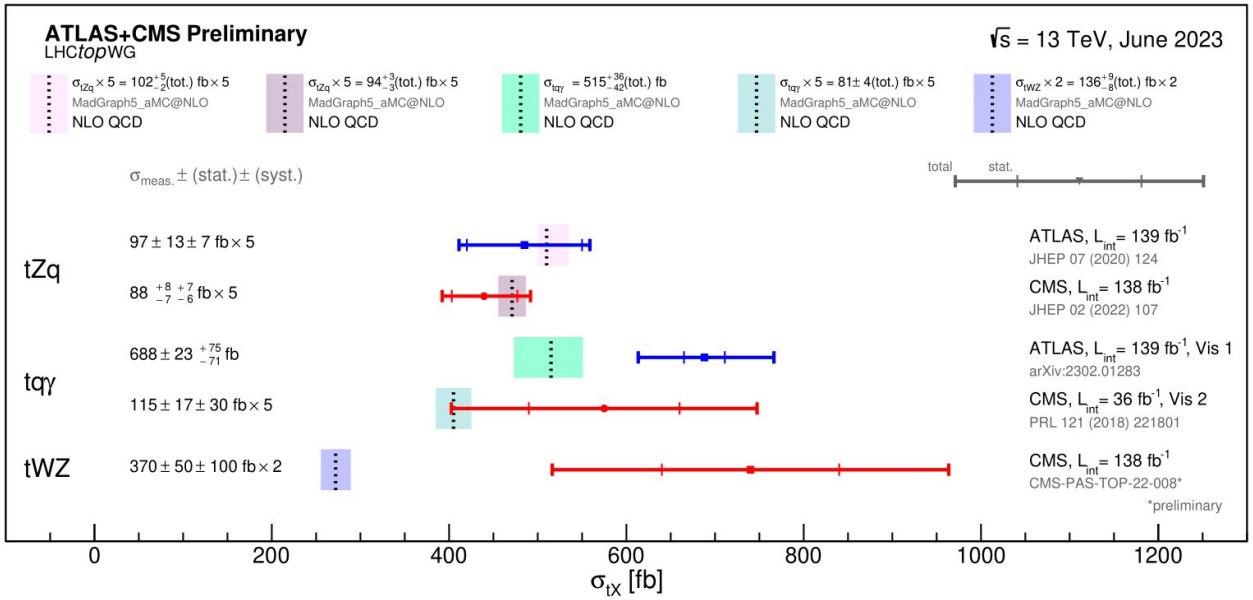
CMS-PAS-TOP-22-008



- Obs. (exp.) significance **3.5σ** (1.4σ) → **first evidence**
- **σ_{tWZ} = 0.37 ± 0.05 (stat) ± 0.10 (syst) pb** (comp. 2.1σ with SM)
- Dominant syst. unc.: ttZ normalization

Summary

- Measurements of associated single top processes done with LHC Run 2 data
  - Already differential measurements of tZq possible
- Still large statistical uncertainties for tqγ and tWZ, more luminosity in Run 3
- Some deviations w.r.t. SM predictions



BACKUP

tZq ATLAS

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ATLAS EXPERIMENT

Common selections			
Exactly 3 leptons (e or μ) with $\|\eta\| < 2.5$ $p_{\mathrm{T}}(\ell_1) > 28\,\mathrm{GeV}$, $p_{\mathrm{T}}(\ell_2) > 20\,\mathrm{GeV}$, $p_{\mathrm{T}}(\ell_3) > 20\,\mathrm{GeV}$ $p_{\mathrm{T}}(\mathrm{jet}) > 35\,\mathrm{GeV}$			
SR 2j1b	CR diboson 2j0b	CR $t\bar{t}$ 2j1b	CR $t\bar{t}Z$ 3j2b
≥ 1 OSSF pair $\|m_{\ell\ell} - m_Z\| < 10\,\mathrm{GeV}$ 2 jets, $\|\eta\| < 4.5$ 1 b-jet, $\|\eta\| < 2.5$	≥ 1 OSSF pair $\|m_{\ell\ell} - m_Z\| < 10\,\mathrm{GeV}$ 2 jets, $\|\eta\| < 4.5$ 0 b-jets	≥ 1 OSDF pair No OSSF pair 2 jets, $\|\eta\| < 4.5$ 1 b-jet, $\|\eta\| < 2.5$	≥ 1 OSSF pair $\|m_{\ell\ell} - m_Z\| < 10\,\mathrm{GeV}$ 3 jets, $\|\eta\| < 4.5$ 2 b-jets, $\|\eta\| < 2.5$
SR 3j1b	CR diboson 3j0b	CR $t\bar{t}$ 3j1b	CR $t\bar{t}Z$ 4j2b
≥ 1 OSSF pair $\|m_{\ell\ell} - m_Z\| < 10\,\mathrm{GeV}$ 3 jets, $\|\eta\| < 4.5$ 1 b-jet, $\|\eta\| < 2.5$	≥ 1 OSSF pair $\|m_{\ell\ell} - m_Z\| < 10\,\mathrm{GeV}$ 3 jets, $\|\eta\| < 4.5$ 0 b-jets	≥ 1 OSDF pair No OSSF pair 3 jets, $\|\eta\| < 4.5$ 1 b-jet, $\|\eta\| < 2.5$	≥ 1 OSSF pair $\|m_{\ell\ell} - m_Z\| < 10\,\mathrm{GeV}$ 4 jets, $\|\eta\| < 4.5$ 2 b-jets, $\|\eta\| < 2.5$

tZq ATLAS

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ATLAS EXPERIMENT

Variable	Rank		Definition
	SR 2j1b	SR 3j1b	
$m_{b\mathrm{j_f}}$	1	1	(Largest) invariant mass of the b-jet and the untagged jet(s)
m_{top}	2	2	Reconstructed top-quark mass
$\lvert\eta(\mathrm{j_f})\rvert$	3	3	Absolute value of the η of the $\mathrm{j_f}$ jet
$m_{\mathrm{T}}(\ell, E_{\mathrm{T}}^{\mathrm{miss}})$	4	4	Transverse mass of the W boson
b-tagging score	5	11	b-tagging score of the b-jet
H_{T}	6	–	Scalar sum of the p_{T} of the leptons and jets in the event
$q(\ell_W)$	7	8	Electric charge of the lepton from the W-boson decay
$\lvert\eta(\ell_W)\rvert$	8	12	Absolute value of the η of the lepton from the W-boson decay
$p_{\mathrm{T}}(W)$	9	15	p_{T} of the reconstructed W boson
$p_{\mathrm{T}}(\ell_W)$	10	14	p_{T} of the lepton from the W-boson decay
$m(\ell\ell)$	11	–	Mass of the reconstructed Z boson
$\lvert\eta(Z)\rvert$	12	13	Absolute value of the η of the reconstructed Z boson
$\Delta R(\mathrm{j_f}, Z)$	13	7	ΔR between the $\mathrm{j_f}$ jet and the reconstructed Z boson
$E_{\mathrm{T}}^{\mathrm{miss}}$	14	–	Missing transverse momentum
$p_{\mathrm{T}}(\mathrm{j_f})$	15	10	p_{T} of the $\mathrm{j_f}$ jet
$\lvert\eta(\mathrm{j_r})\rvert$	–	5	Absolute value of the η of the $\mathrm{j_r}$ jet
$p_{\mathrm{T}}(Z)$	–	6	p_{T} of the reconstructed Z boson
$p_{\mathrm{T}}(\mathrm{j_r})$	–	9	p_{T} of the $\mathrm{j_r}$ jet

tZq ATLAS

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	SR 2j1b	CR diboson 2j0b	CR $t\bar{t}$ 2j1b	CR $t\bar{t}Z$ 3j2b
tZq	79 ± 11	53.1 ± 7.5	0.2 ± 0.1	12.9 ± 2.0
$t\bar{t} + tW$	23.8 ± 4.8	13.7 ± 2.7	33.3 ± 6.3	1.7 ± 0.3
Z + jets	28 ± 13	181 ± 82	< 0.1	1.4 ± 0.6
VV + LF	19.7 ± 7.9	2000 ± 100	< 0.1	0.1 ± 0.1
VV + HF	101 ± 22	383 ± 78	0.4 ± 0.1	5.2 ± 1.7
$t\bar{t}Z + tWZ$	96 ± 11	63.2 ± 7.0	4.8 ± 0.5	59.3 ± 7.1
$t\bar{t}H + t\bar{t}W$	6.5 ± 1.0	3.0 ± 0.5	12.4 ± 1.9	2.8 ± 0.5
Total	354 ± 16	2697 ± 56	51.1 ± 6.1	83.5 ± 6.4
Data	359	2703	49	92

	SR 3j1b	CR diboson 3j0b	CR $t\bar{t}$ 3j1b	CR $t\bar{t}Z$ 4j2b
tZq	43.4 ± 6.2	21.2 ± 3.3	0.2 ± 0.1	8.0 ± 1.3
$t\bar{t} + tW$	11.0 ± 2.2	6.9 ± 1.3	15.4 ± 3.1	1.0 ± 0.2
Z + jets	12.8 ± 6.0	53 ± 23	< 0.1	0.4 ± 0.2
VV + LF	10.1 ± 4.2	624 ± 53	< 0.1	0.1 ± 0.1
VV + HF	58 ± 17	186 ± 51	0.3 ± 0.1	3.4 ± 1.0
$t\bar{t}Z + tWZ$	132 ± 12	61.9 ± 6.2	3.9 ± 0.5	58.1 ± 5.3
$t\bar{t}H + t\bar{t}W$	4.7 ± 0.7	1.7 ± 0.3	8.2 ± 1.3	2.0 ± 0.3
Total	272 ± 12	955 ± 29	28.0 ± 3.0	72.8 ± 5.0
Data	259	949	31	75

tZq ATLAS

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Uncertainty source	$\Delta\sigma/\sigma$ [%]
Prompt-lepton background modelling and normalisation	3.3
Jets and $E_{\mathrm{T}}^{\mathrm{miss}}$ 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

tZq CMS

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Observable	Parton level				Particle level			
	Absolute		Normalized		Absolute		Normalized	
	4FS	5FS	4FS	5FS	4FS	5FS	4FS	5FS
$p_{\mathrm{T}}(\mathrm{Z})$	97.7	84.6	99.8	99.3	97.7	89.1	99.8	99.8
$\Delta\phi(\ell,\ell')$	73.1	54.1	65.5	61.6	75.7	65.6	69.2	70.9
$p_{\mathrm{T}}(\ell_{\mathrm{t}})$	94.5	74.4	93.3	90.9	95.0	77.1	94.3	89.5
$m(3\ell)$	7.0	2.0	5.4	4.5	7.3	2.2	3.9	3.3
$p_{\mathrm{T}}(\mathrm{t})$	74.4	68.2	74.1	76.4	72.8	70.5	71.1	73.6
$m(\mathrm{t},\mathrm{Z})$	65.0	48.3	56.8	51.6	66.3	64.0	58.2	67.3
$\cos(\theta^{\star}_{\mathrm{pol}})$	84.6	63.1	80.7	83.7	88.2	71.8	87.4	91.8
$p_{\mathrm{T}}(\mathrm{j}')$	—	—	—	—	44.2	44.1	35.8	41.5
$\lvert\eta(\mathrm{j}')\rvert$	—	—	—	—	46.2	30.4	29.0	24.3

tZq CMS

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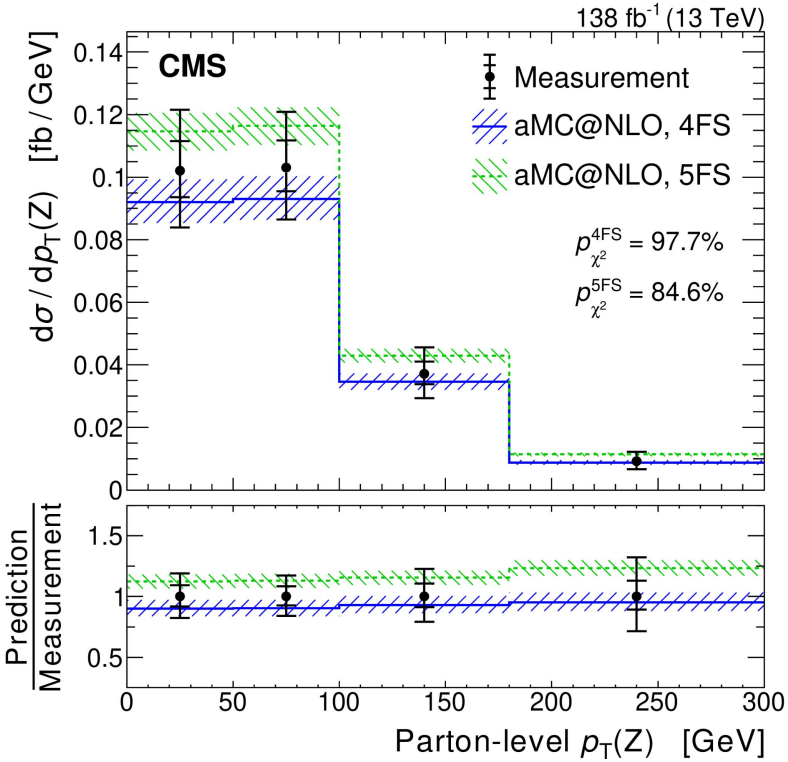

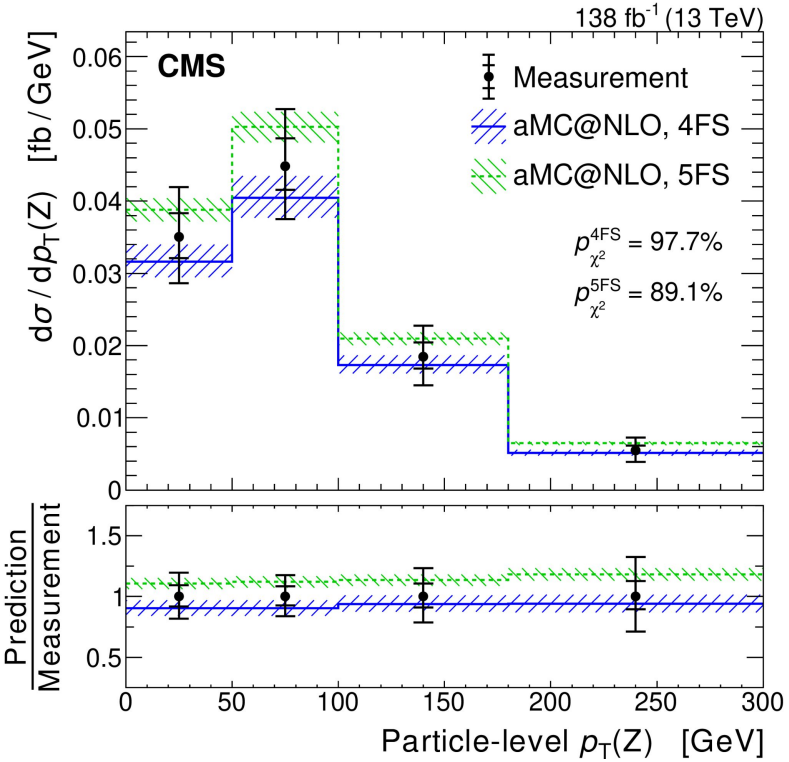

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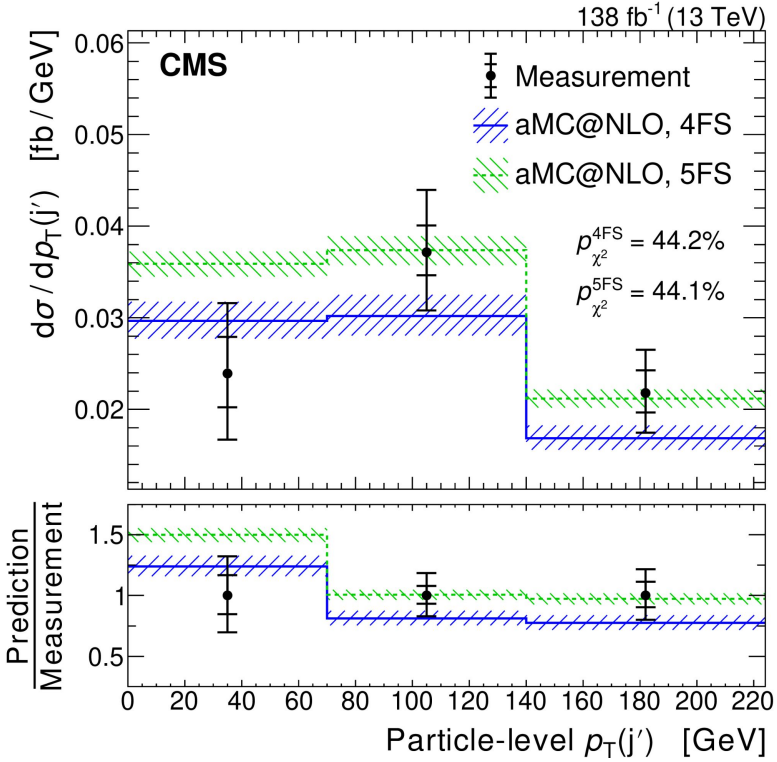

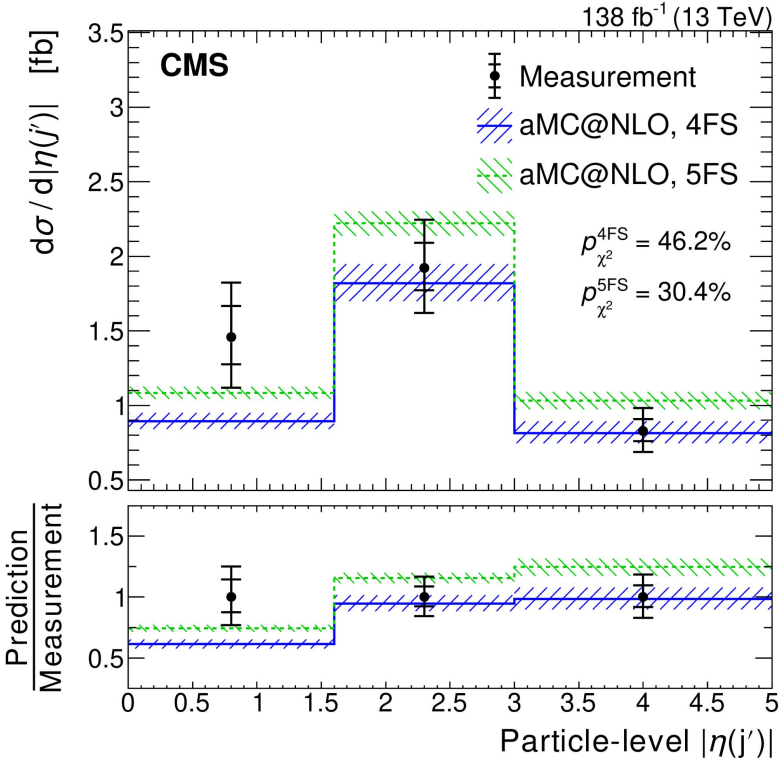

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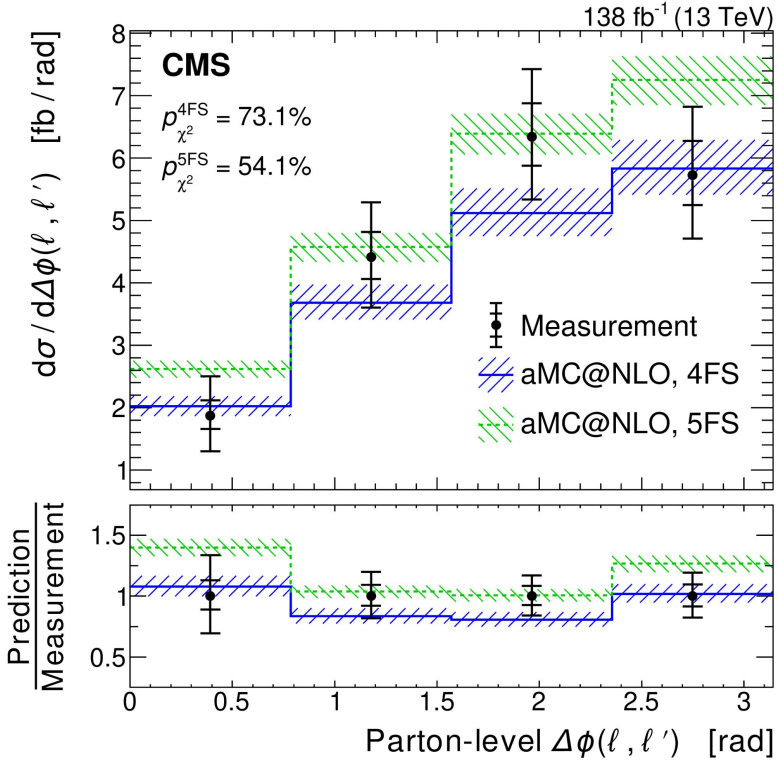

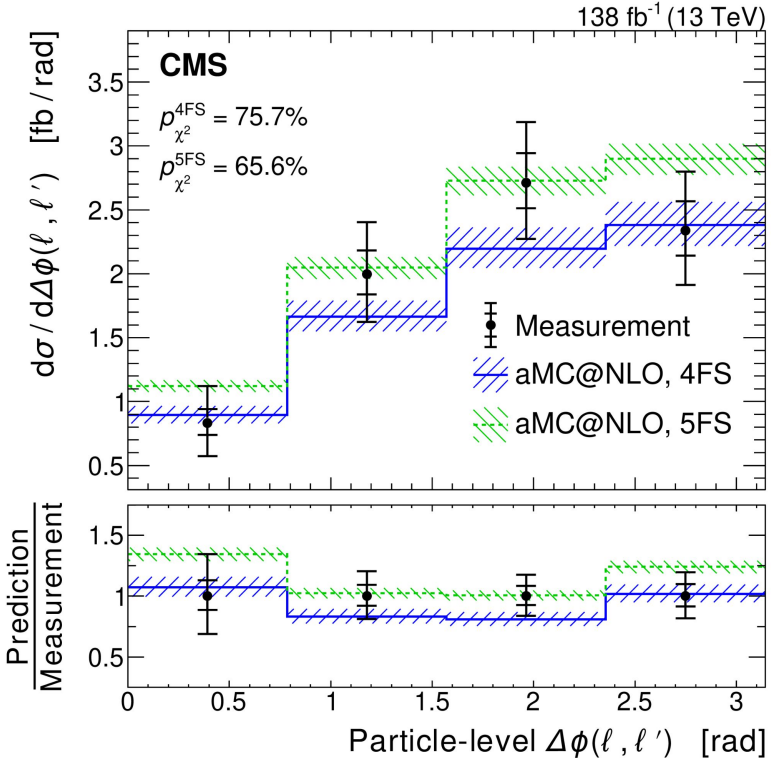

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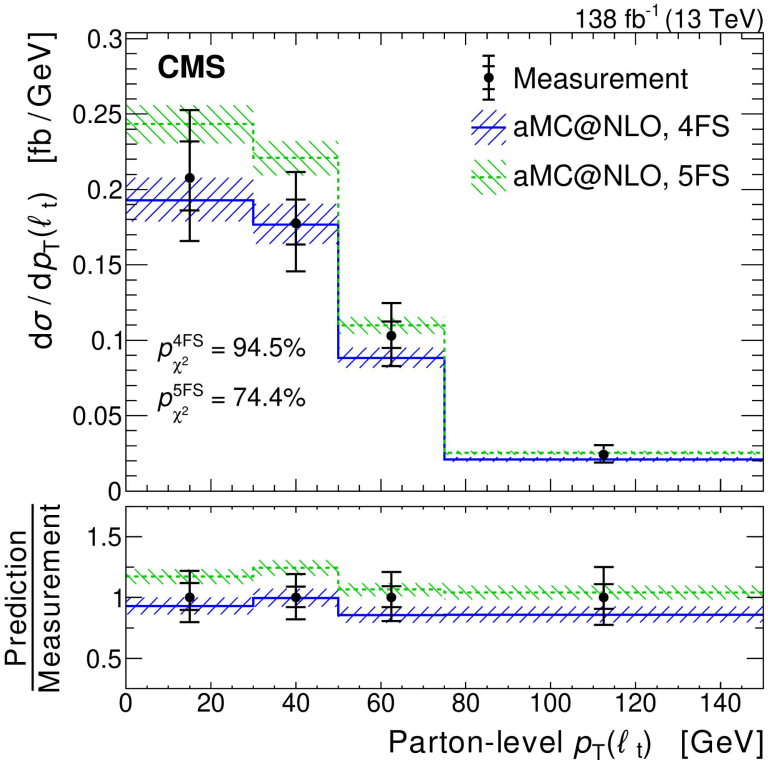

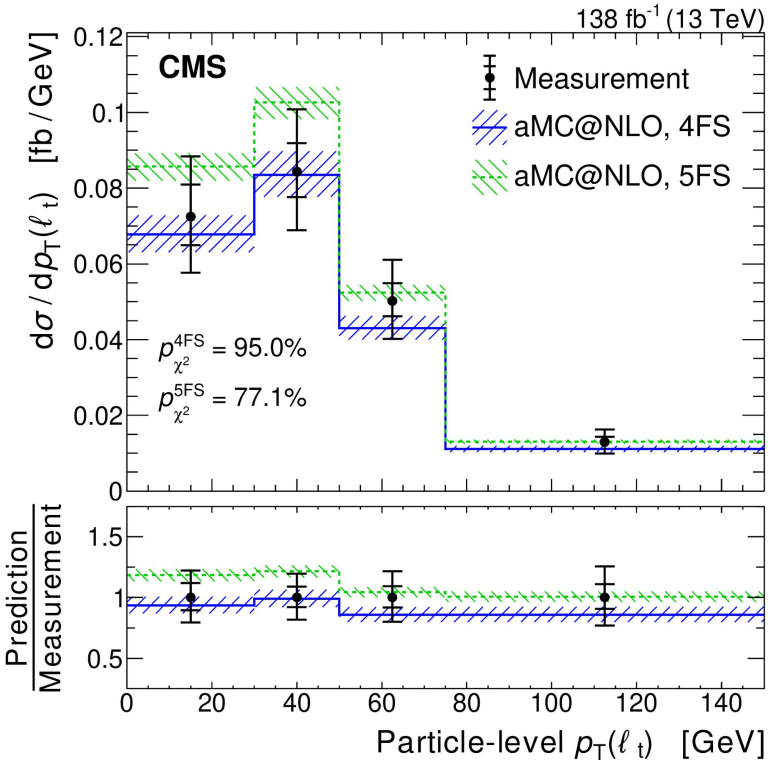

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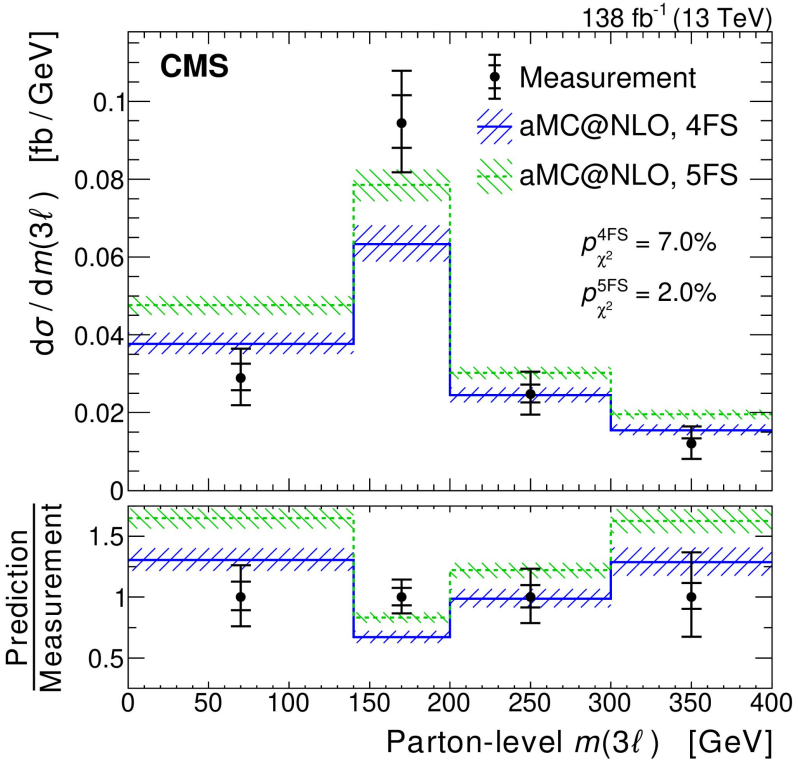

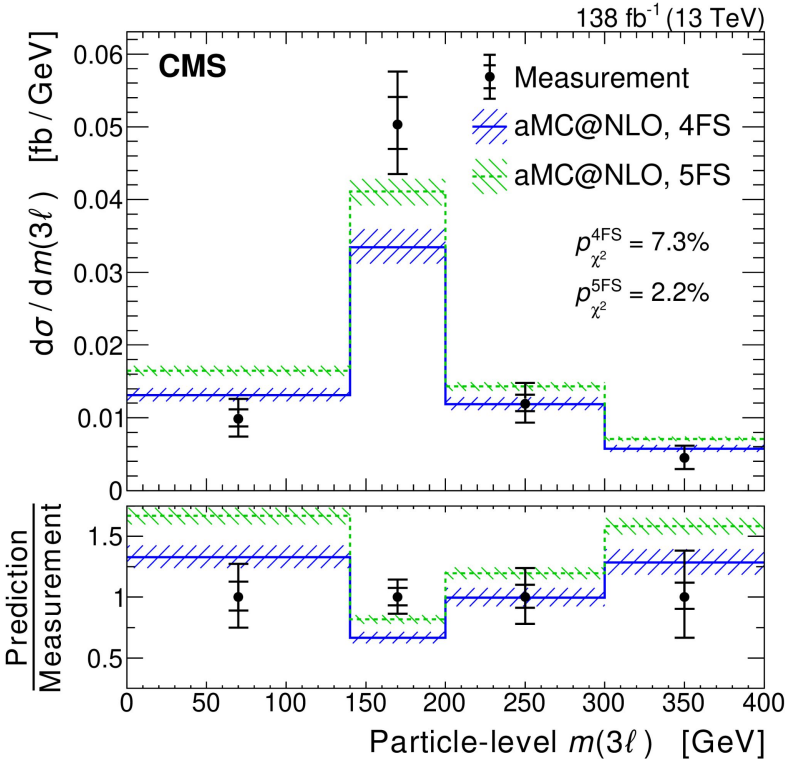

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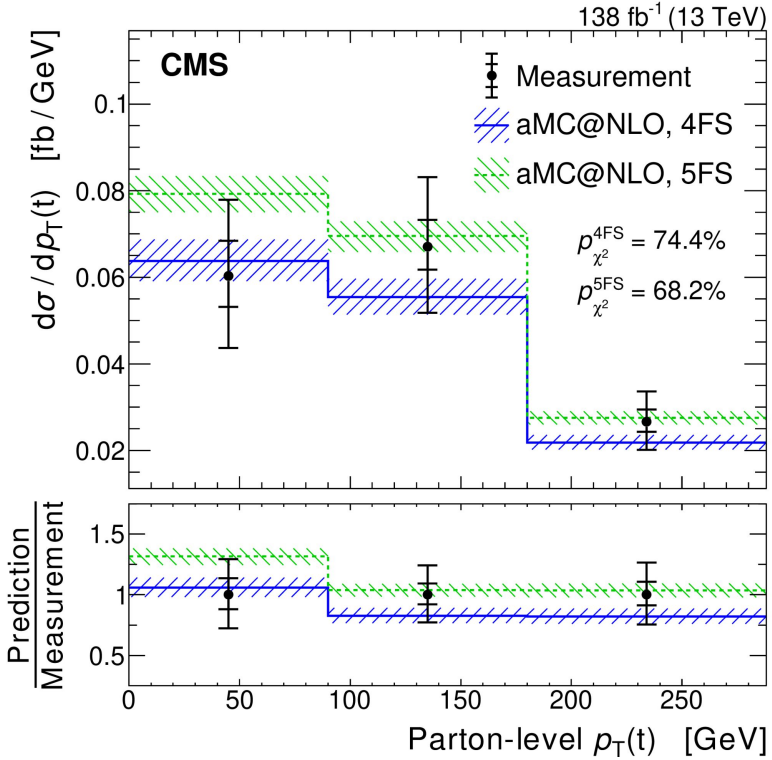

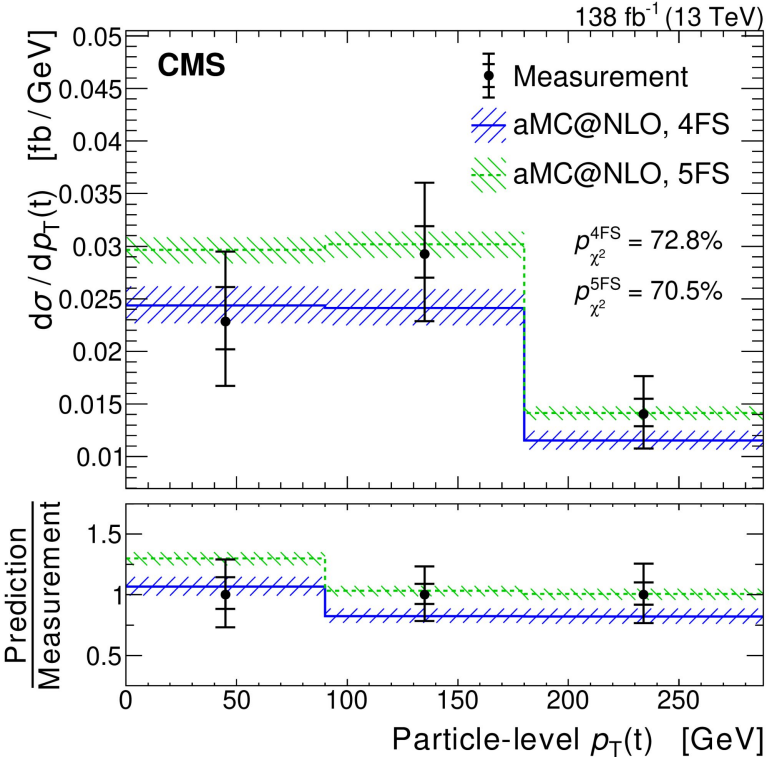

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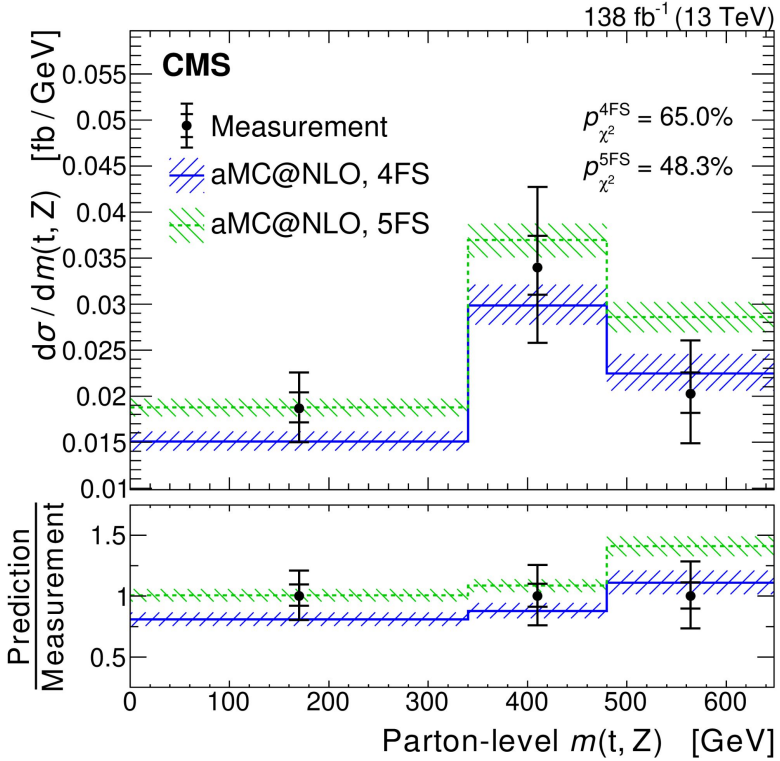

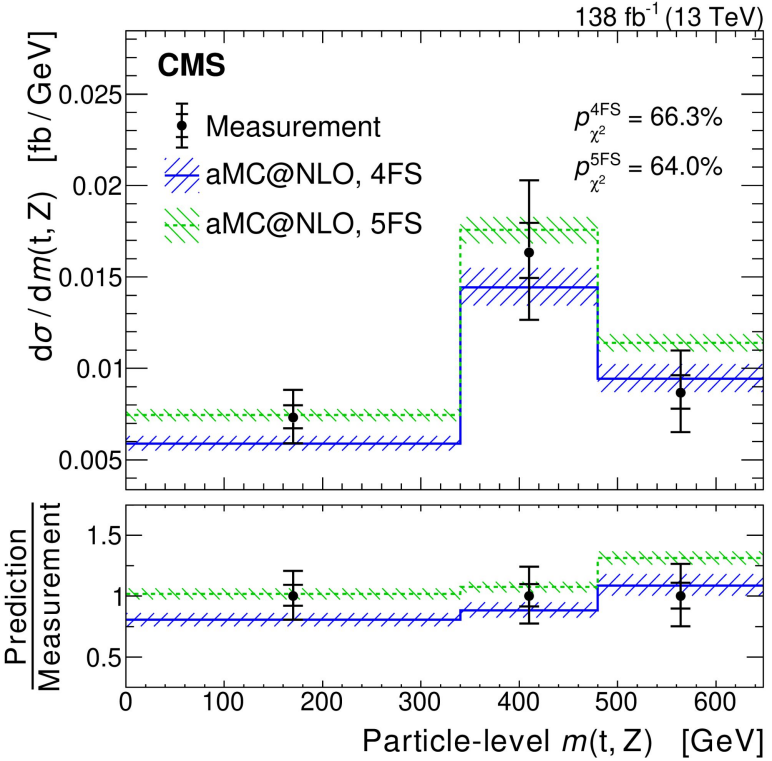

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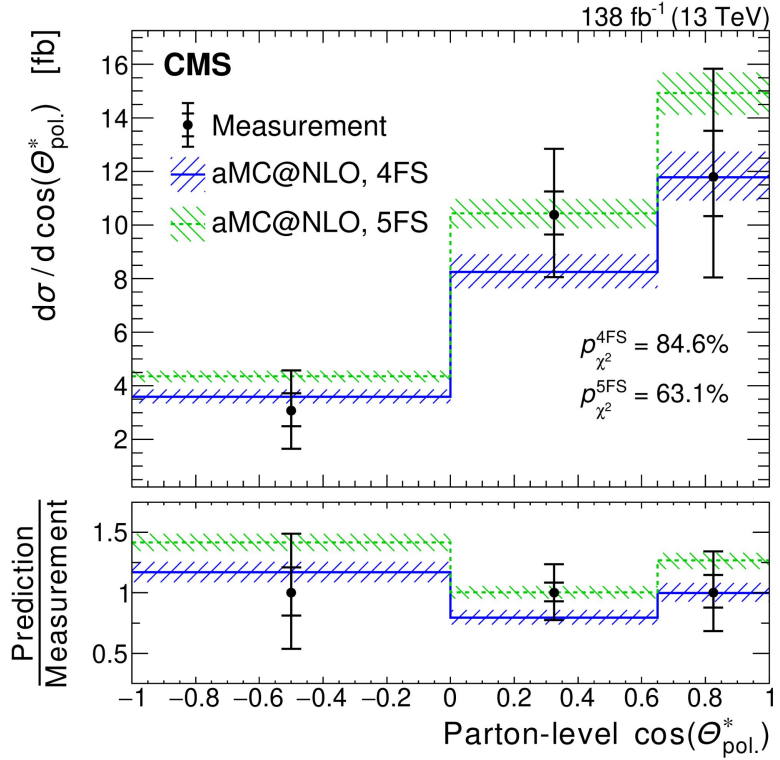

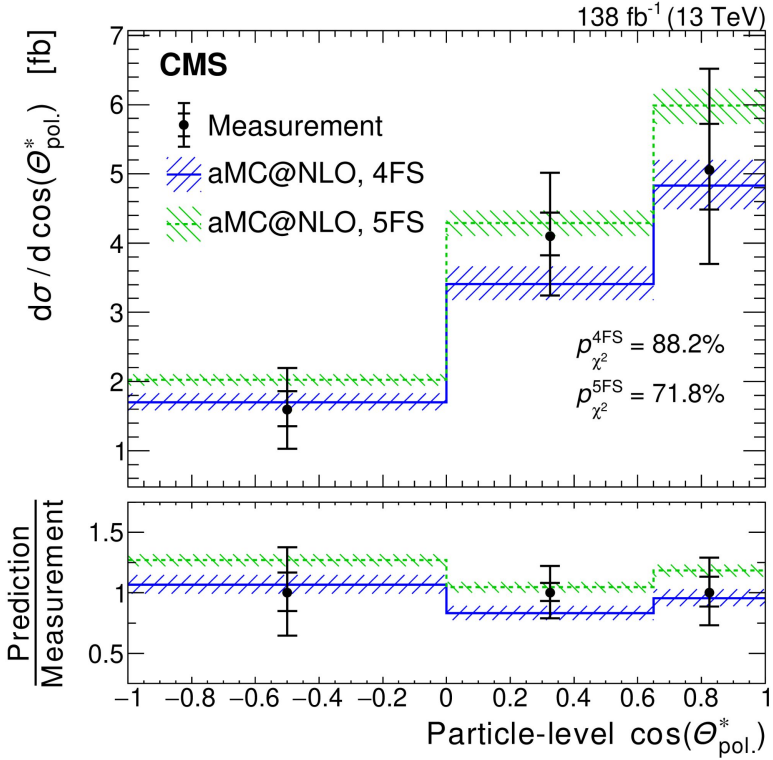

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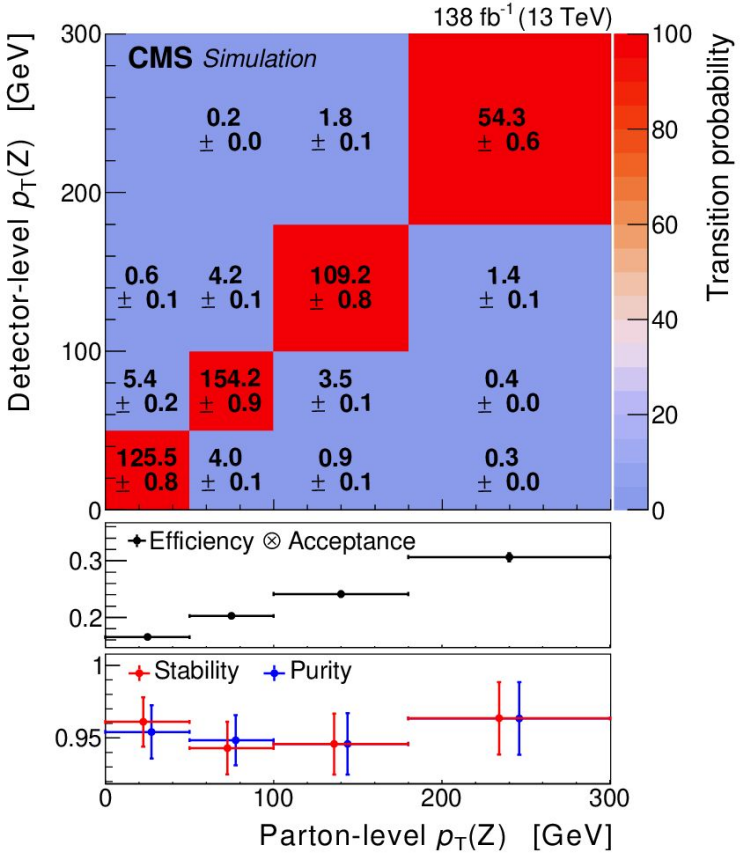
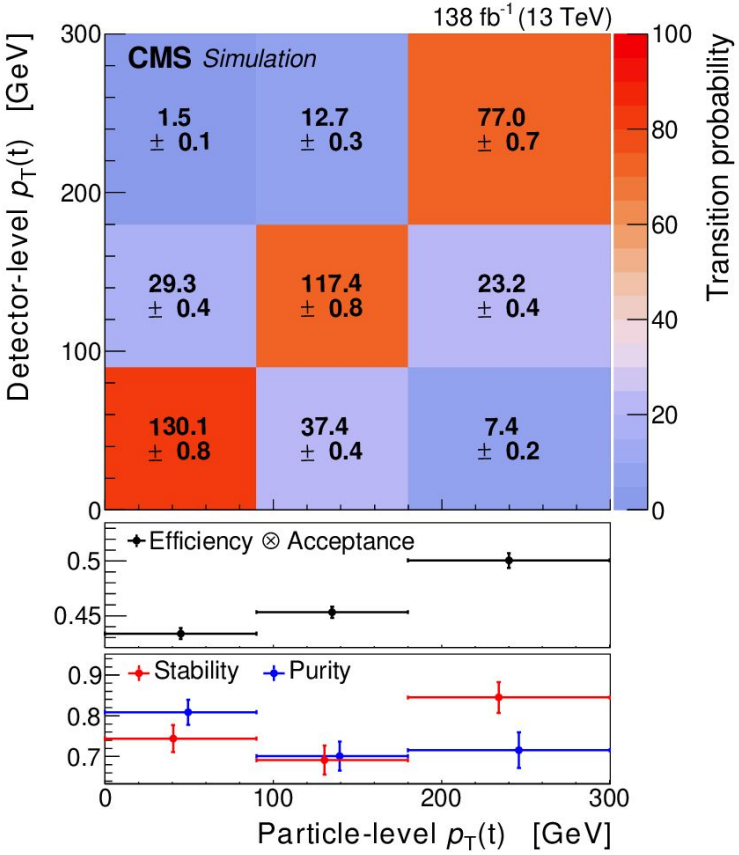




tqγ CMS

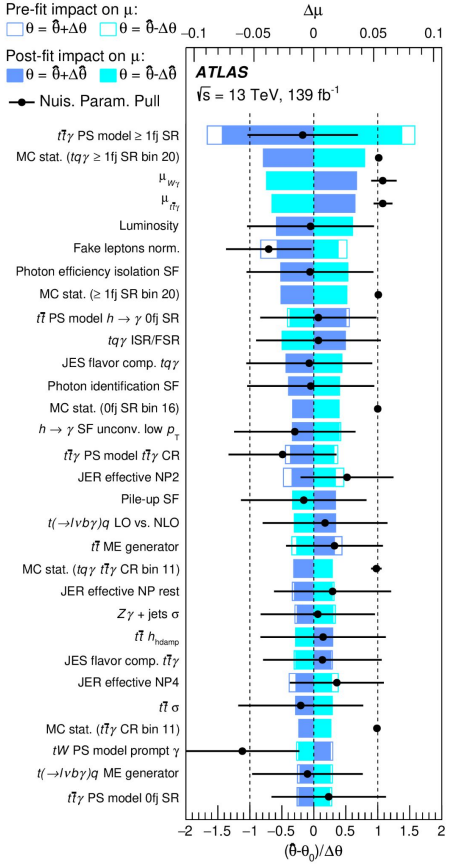
PRL 121 (2018) 221802

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

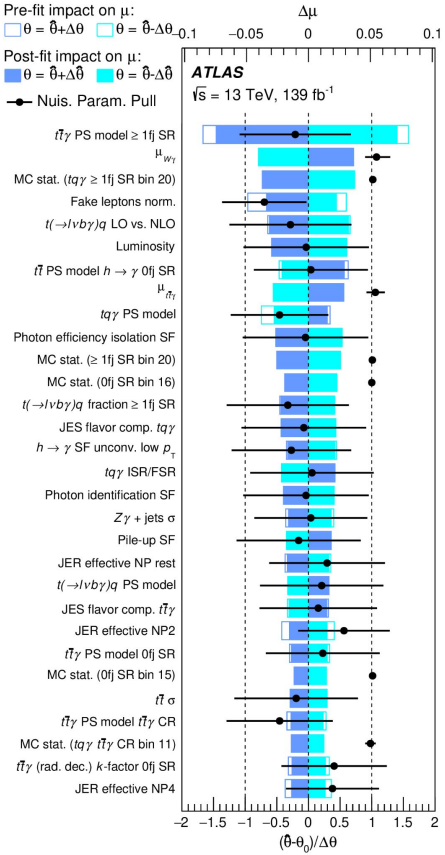
tqγ ATLAS

arXiv:2302.01283
Submitted to PRL

parton-level



particle-level



particle-level

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ATLAS EXPERIMENT

parton-level	≥ 1fj SR	0fj SR	$t\bar{t}\gamma$ CR	$W\gamma$ CR
$tq\gamma$	2410 ± 250	2500 ± 320	890 ± 120	1290 ± 150
$t\,(\to \ell\nu b\gamma)\,q$	370 ± 160	460 ± 230	130 ± 50	230 ± 110
$t\bar{t}\gamma$ (production)	3200 ± 500	4800 ± 700	4300 ± 600	2700 ± 400
$t\bar{t}\gamma$ (radiative decay)	3900 ± 600	9400 ± 1400	5700 ± 600	4300 ± 900
$W\gamma$+jets	2500 ± 400	9200 ± 1400	1160 ± 320	31 800 ± 3000
$Z\gamma$+jets	980 ± 310	2700 ± 800	430 ± 150	7700 ± 2400
$e \to \gamma$ fake photons	5100 ± 500	10 300 ± 800	4800 ± 400	5400 ± 500
$h \to \gamma$ fake photons	1100 ± 400	2600 ± 900	1300 ± 500	2500 ± 800
Other prompt γ	1330 ± 350	2600 ± 900	1300 ± 400	4000 ± 600
Fake leptons	390 ± 190	1000 ± 500	110 ± 50	3500 ± 1700
Total	21 250 ± 150	45 720 ± 250	20 180 ± 150	63 590 ± 280
Data	21 227	45 723	20 194	63 592

tqγ ATLAS

arXiv:2302.01283
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ATLAS EXPERIMENT

particle-level	≥ 1fj SR	0fj SR	$t\bar{t}\gamma$ CR	$W\gamma$ CR
$tq\gamma$	2360 ± 250	2450 ± 310	880 ± 120	1260 ± 140
$t\,(\to \ell\nu b\gamma)\,q$	500 ± 170	660 ± 210	180 ± 60	330 ± 120
$t\bar{t}\gamma$ (production)	3100 ± 400	4700 ± 700	4300 ± 600	2700 ± 400
$t\bar{t}\gamma$ (radiative decay)	3800 ± 600	9200 ± 1400	5600 ± 600	4200 ± 900
$W\gamma$+jets	2500 ± 400	9200 ± 1400	1170 ± 320	31 700 ± 3000
$Z\gamma$+jets	970 ± 310	2700 ± 800	430 ± 150	7700 ± 2400
$e \to \gamma$ fake photons	5100 ± 500	10 400 ± 800	4900 ± 400	5500 ± 500
$h \to \gamma$ fake photons	1100 ± 400	2700 ± 900	1300 ± 500	2600 ± 800
Other prompt γ	1340 ± 350	2600 ± 900	1400 ± 400	4000 ± 600
Fake leptons	390 ± 190	1000 ± 500	110 ± 50	3600 ± 1700
Total	21 250 ± 150	45 720 ± 240	20 180 ± 150	63 590 ± 280
Data	21 227	45 723	20 194	63 592

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ATLAS EXPERIMENT

parton-level

Uncertainty	$\Delta\sigma/\sigma$
$t\bar{t}\gamma$ modeling	±5.5%
Background MC statistics	±3.5%
$tq\gamma$ MC statistics	±3.3%
$t\bar{t}$ modeling	±2.4%
$tq\gamma$ modeling	±2.0%
$t\,(\to \ell\nu b\gamma)\,q$ modeling	±1.9%
Additional background uncertainties	±1.9%
$t\,(\to \ell\nu b\gamma)\,q$ MC statistics	±0.3%
$h \to \gamma$ photon fakes	±2.0%
Lepton fakes	±1.9%
$e \to \gamma$ photon fakes	±0.6%
Luminosity	±2.2%
Pileup	±1.2%
Jets and $E_{\mathrm{T}}^{\mathrm{miss}}$	±3.6%
Photons	±2.5%
Leptons	±0.9%
b-tagging	±0.9%
Total systematic uncertainty	±10.6%

particle-level

Uncertainty	$\Delta\sigma/\sigma$
$t\bar{t}\gamma$ modeling	±5.5%
Background MC statistics	±3.6%
$t\,(\to \ell\nu b\gamma)\,q$ modeling	±3.3%
$tq\gamma$ MC statistics	±3.0%
$t\bar{t}$ modeling	±2.3%
$tq\gamma$ modeling	±2.3%
Additional background uncertainties	±2.0%
$t\,(\to \ell\nu b\gamma)\,q$ MC statistics	±0.3%
Lepton fakes	±2.2%
$h \to \gamma$ photon fakes	±2.1%
$e \to \gamma$ photon fakes	±0.6%
Luminosity	±2.2%
Pileup	±1.3%
Jets and $E_{\mathrm{T}}^{\mathrm{miss}}$	±3.5%
Photons	±2.5%
Leptons	±0.9%
b-tagging	±0.7%
Total systematic uncertainty	±10.7%

tqγ ATLAS

arXiv:2302.01283
Submitted to PRL

ATLAS EXPERIMENT

Input feature	Used in 0fj SR NN	Used in ≥ 1fj SR NN
$\eta(\gamma)$	✓	
$p_{\mathrm{T}}(\ell)$	✓	
$\eta(\ell)$	✓	
Is ℓ an electron or muon?		✓
$p_{\mathrm{T}}(b)$	✓	✓
$\eta(b)$	✓	
b-tagging bin	✓	✓
$p_{\mathrm{T}}(\mathrm{fj})$		✓
m_t	✓	✓
H_{T}	✓	✓
$\Delta R(\gamma, \ell)$	✓	✓
$p_{\mathrm{T}}(t, \gamma)$	✓	
$m_{\mathrm{T}}(\ell, E_{\mathrm{T}}^{\mathrm{miss}})$		✓
$\Delta R(\ell, b)$	✓	✓
$m(\ell, b)$		✓
$m_{\mathrm{T}}(\gamma, \ell, E_{\mathrm{T}}^{\mathrm{miss}})$	✓	✓
$E(\gamma, \mathrm{fj})$		✓
$\Delta\eta(\gamma, \mathrm{fj})$		✓
$\Delta R(\ell, \mathrm{fj})$		✓
$m(b, \mathrm{fj})$		✓