Rare Top Production at the LHC

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On behalf of CMS and ATLAS Collaborations

Les Rencontres de Physique de la Vallée d'Aoste
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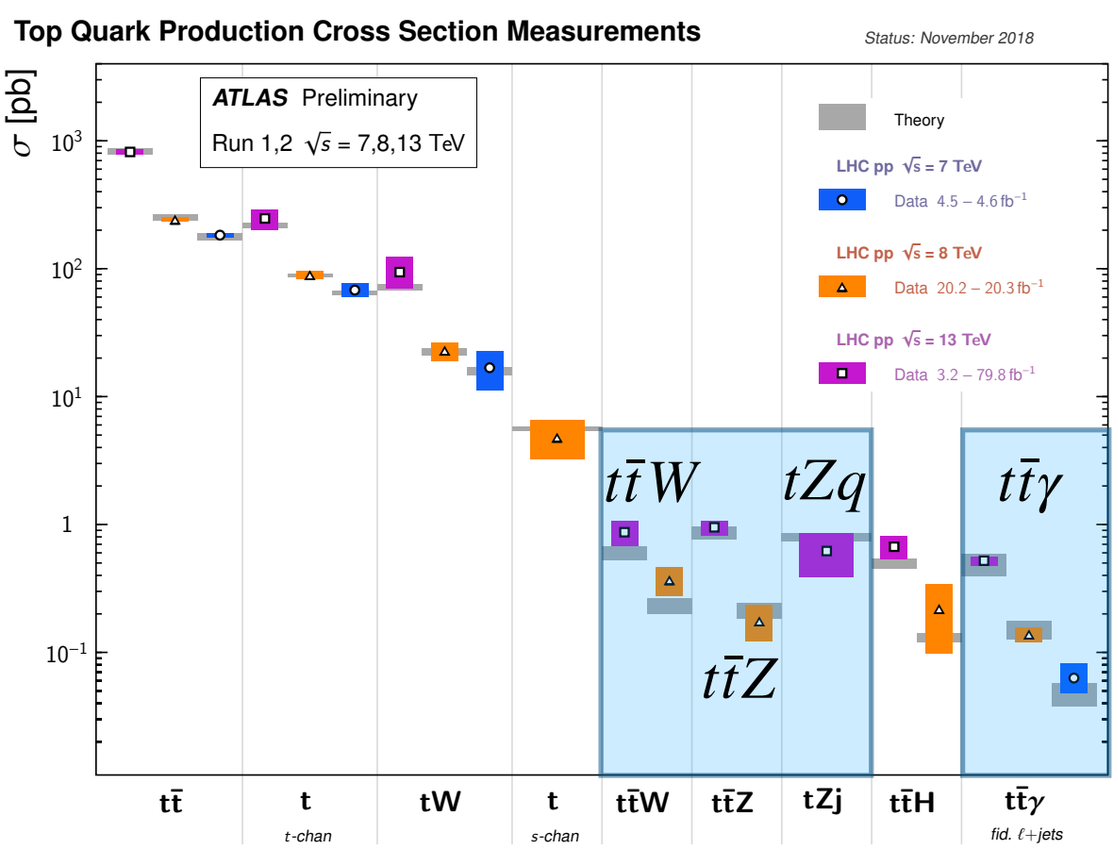
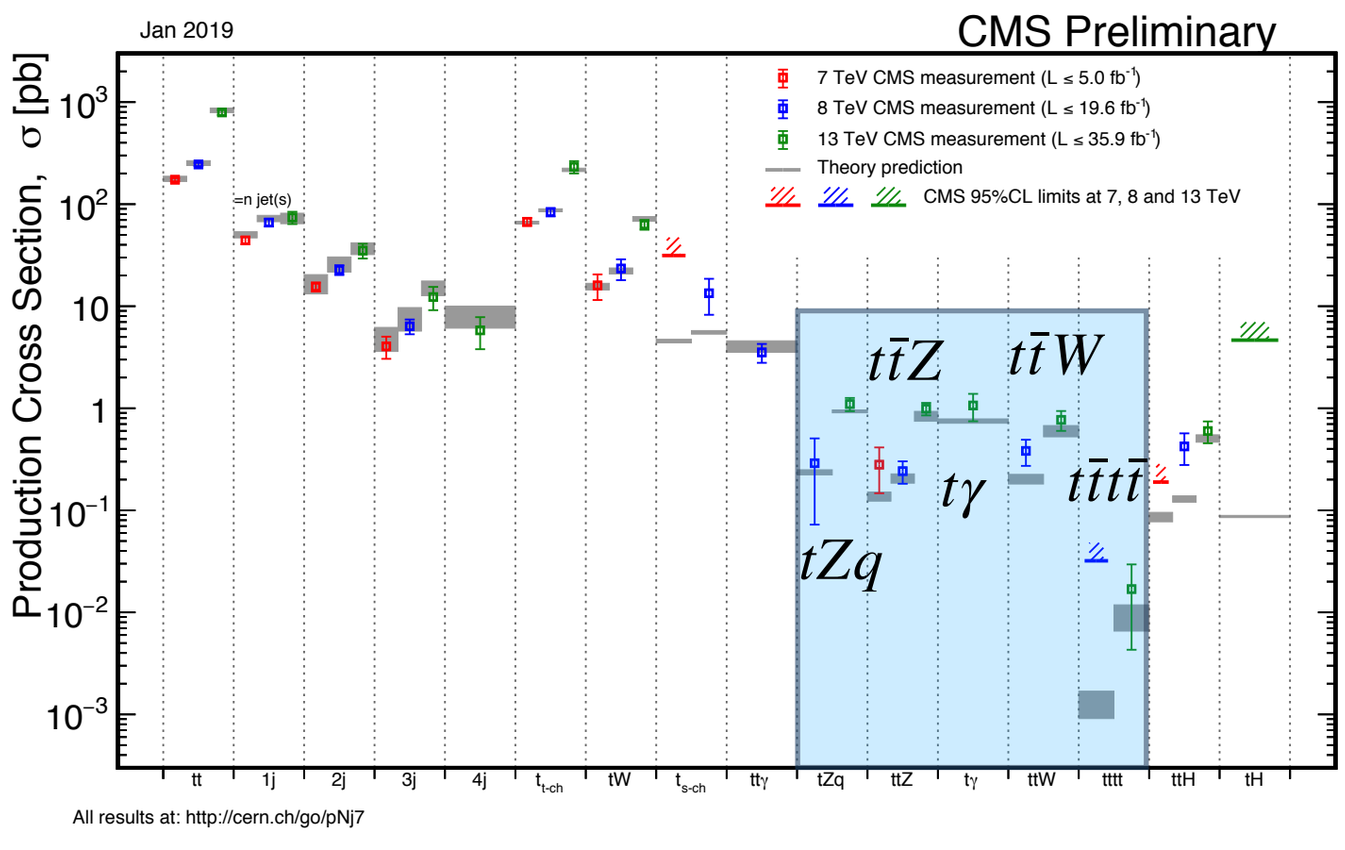
Rare Top Production

- LHC is a “top factory” allowing precise measurement of top quark production
- Many rare top production mechanisms within the reach of the LHC with Run 2
- Present recent results of some of these measurements from CMS and ATLAS

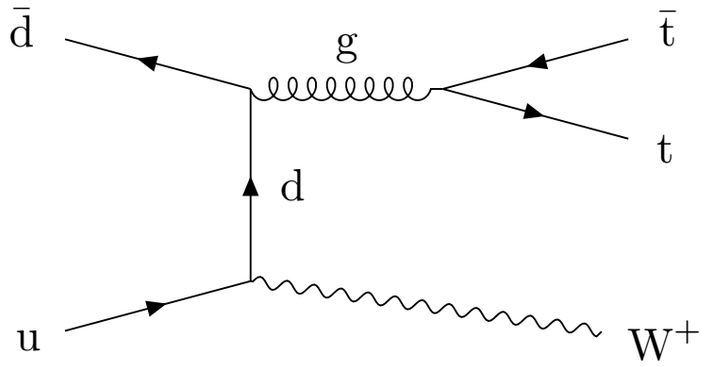
- **ttW**
- **ttZ**
- **ttγ**
- **tZq**
- **tγ**
- **Four top**
- **FCNC decays**



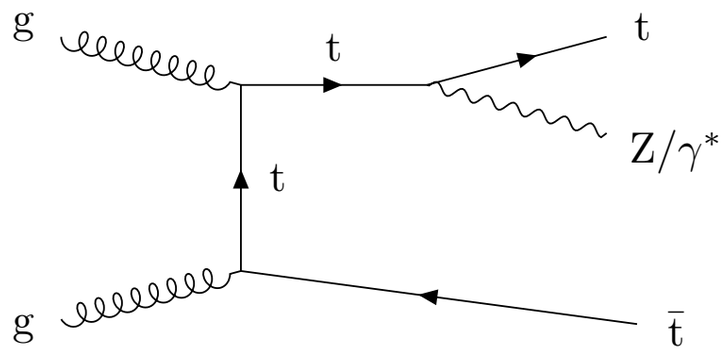


All results at: http://cern.ch/go/pNj7

ttW/ttZ Production



$$\sigma^{\mathrm{NLO}}_{\mathrm{t\bar{t}W}} = 0.628 \pm 0.082 \text{ pb}^{[1]}$$



$$\sigma^{\mathrm{NLO}}_{\mathrm{t\bar{t}Z}} = 0.839 \pm 0.101 \text{ pb}^{[1]}$$

- SM ttW and ttZ production are very interesting measurements
  - Some of the heaviest final states observed at LHC
  - ttZ production directly probes top electroweak coupling
- Receive significant enhancements in BSM models
- Signatures are background to many SM measurements and BSM searches

[1] arXiv:1610.07922

2015/16 Dataset
36.1 fb^{-1}

ttW/ttZ ATLAS

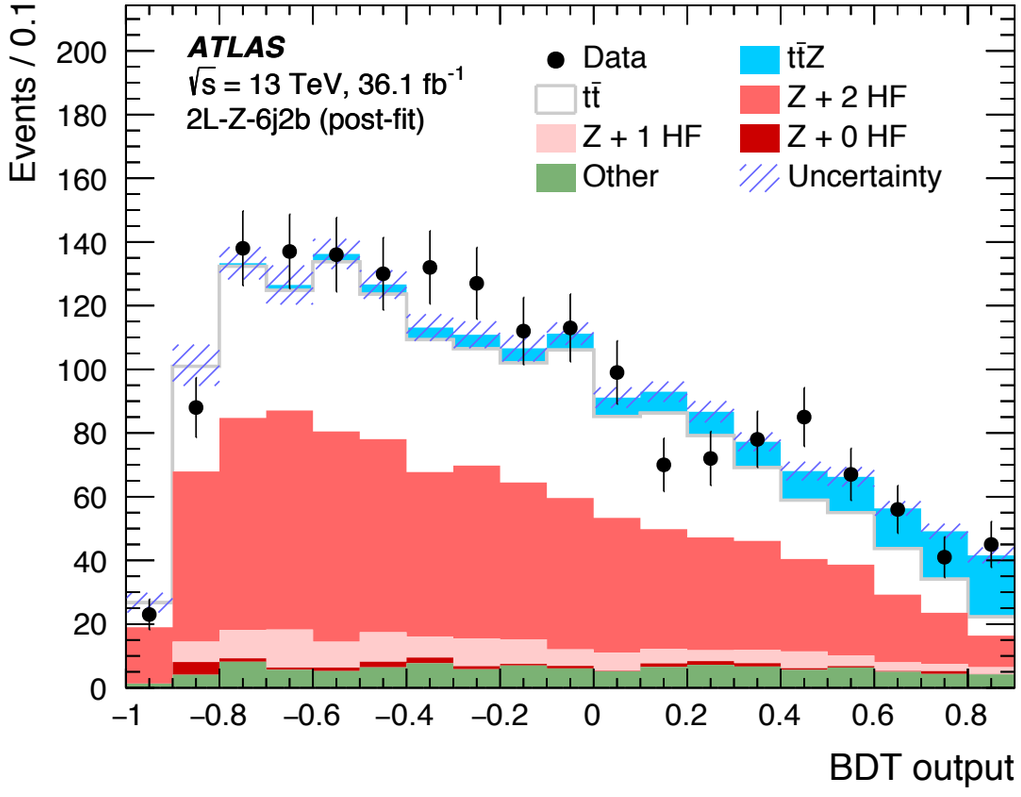
ATLAS EXPERIMENT

Measurement in multi-lepton final states

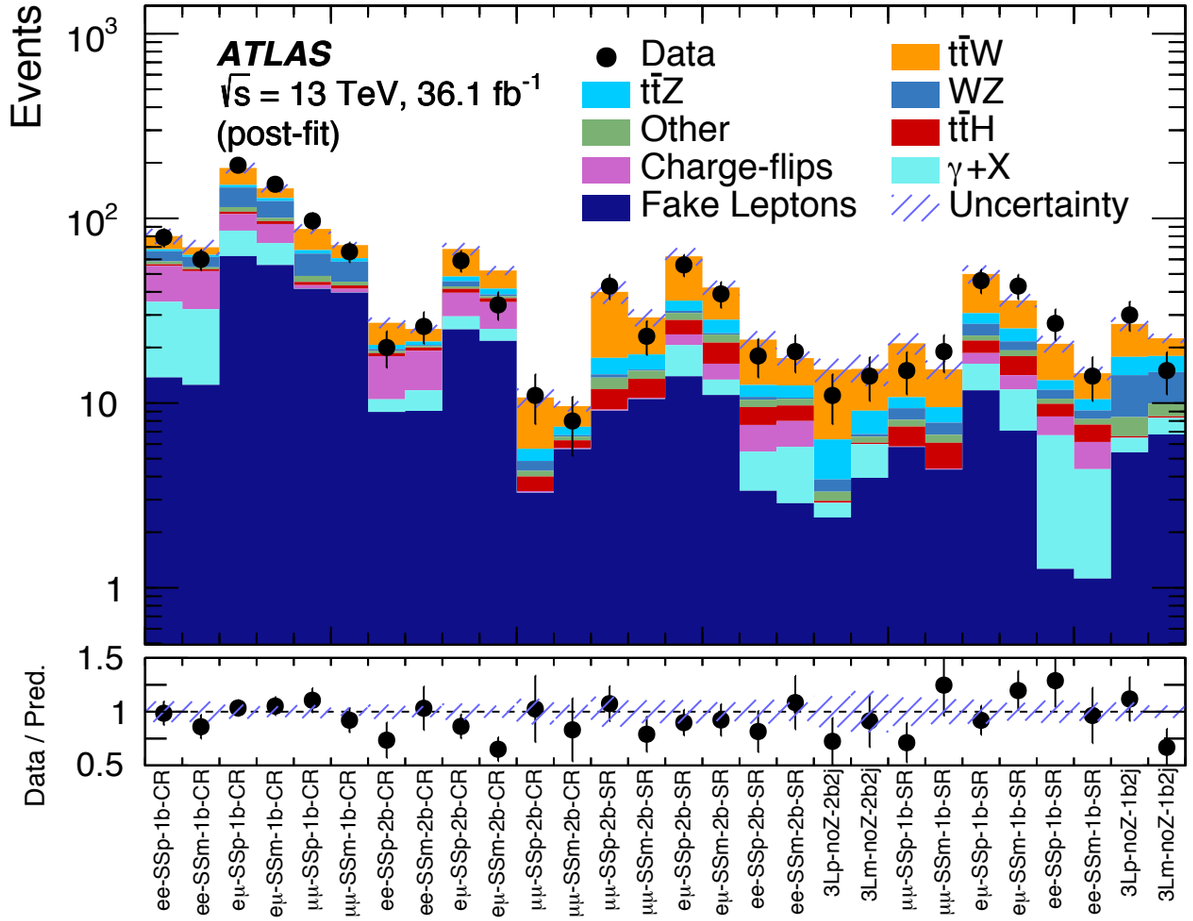
Process	$t\bar{t}$ decay	Boson decay	Channel
$t\bar{t}W$	$(\ell^{\pm}\nu b)(q\bar{q}b)$	$\ell^{\pm}\nu$	SS dilepton
	$(\ell^{\pm}\nu b)(\ell^{\mp}\nu b)$	$\ell^{\pm}\nu$	Trilepton
$t\bar{t}Z$	$(q\bar{q}b)(q\bar{q}b)$	$\ell^{+}\ell^{-}$	OS dilepton
	$(\ell^{\pm}\nu b)(q\bar{q}b)$	$\ell^{+}\ell^{-}$	Trilepton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

- Main backgrounds vary by channel
  - OS 2ℓ: tt, Z+jets
  - SS 2ℓ: Fake leptons and charge misID
  - 3ℓ/4ℓ: Diboson, Fake leptons, t+Z, t+WZ
- Events split into signal regions based on jet/b-jet/lepton multiplicities

BDT discriminant in OS 2ℓ



Event yields used in other channels



arXiv:1901.03584 (submitted to PRD)

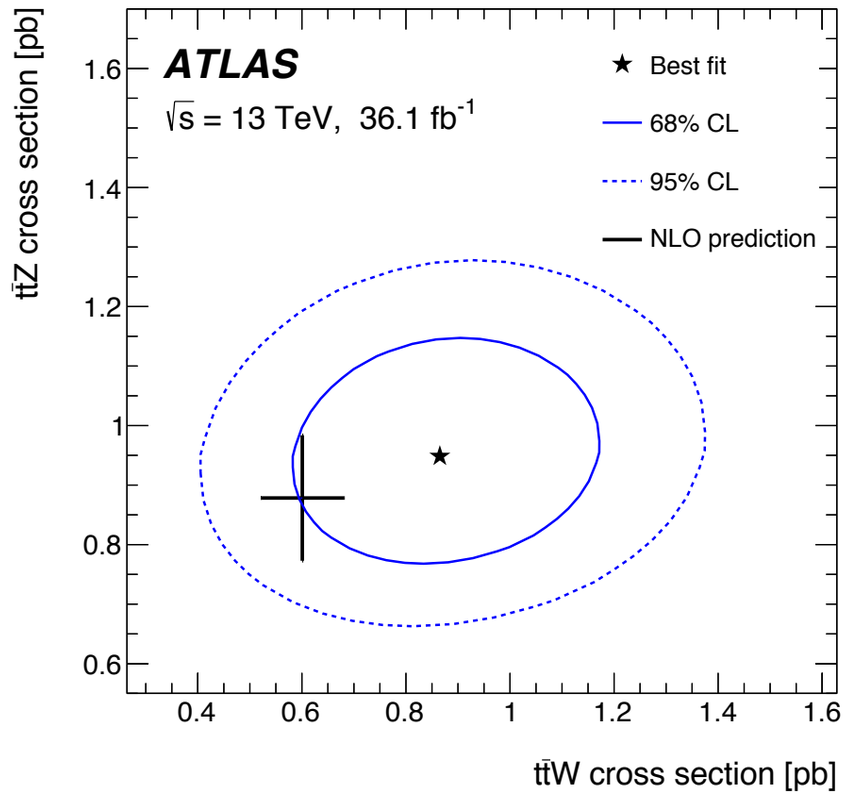
2015/16 Dataset
36.1 fb^{-1}

ttW/ttZ ATLAS

- Simultaneous fit to BDT discriminants in OS 2ℓ and event yields in other regions

$$\sigma_{t\bar{t}Z} = 0.95 \pm 0.08(\text{stat.}) \pm 0.10(\text{syst.})\text{pb}$$
$$\sigma_{t\bar{t}W} = 0.87 \pm 0.13(\text{stat.}) \pm 0.14(\text{syst.})\text{pb}$$

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	–



- Limited by statistics and systematic uncertainties dominated by
  - ttZ: Signal modeling, background simulation modeling, and flavor tagging
  - ttW: Signal modeling, data-driven background statistics, fake leptons and charge misID

arXiv:1901.03584 (submitted to PRD)

2015/16 Dataset
36.1 fb^{-1}

ttW/ttZ

- Simultaneous fit to BDT discriminants in OS 2ℓ and event yields in other regions

$$\sigma_{t\bar{t}Z} = 0.95 \pm 0.08(\text{stat.}) \pm 0.10(\text{syst.})\text{pb}$$
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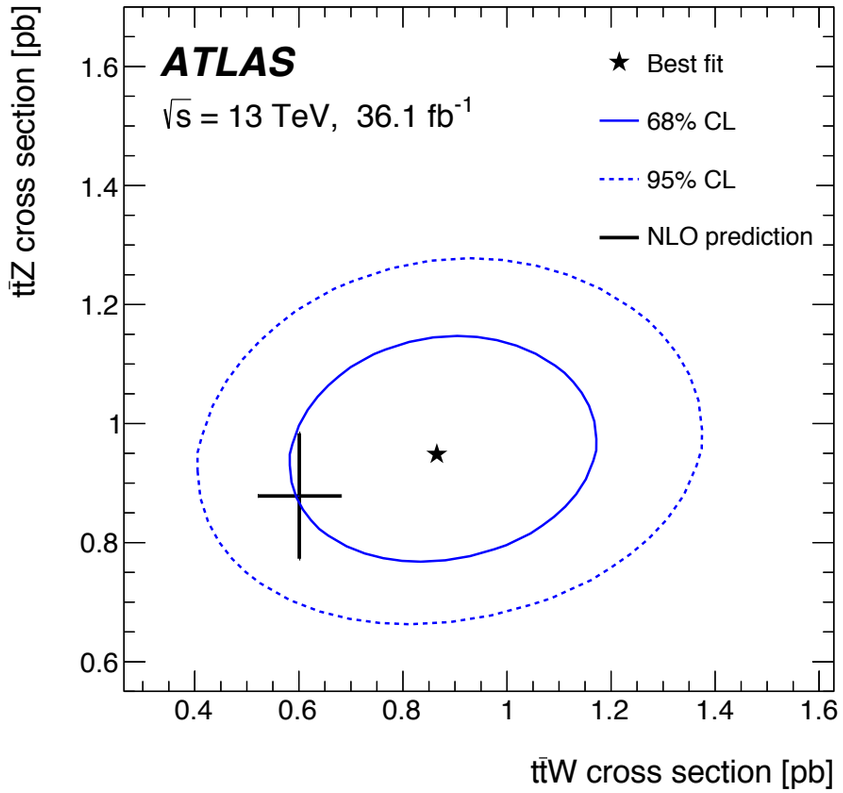
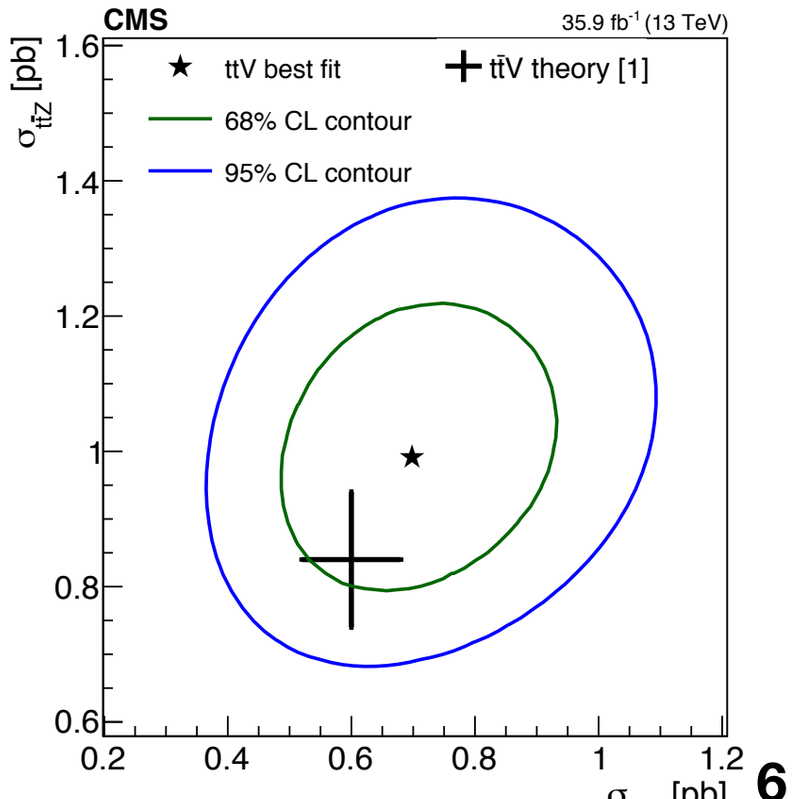
Fit configuration	$\mu_{t\bar{t}Z}$	$\mu_{t\bar{t}W}$



2016 Dataset
35.9 fb^{-1}

JHEP 08 (2018) 011 (arXiv:1711.02547)

$$\sigma_{\mathrm{t\bar{t}Z}} = 0.99^{+0.09}_{-0.08}\,(\text{stat})^{+0.12}_{-0.10}\,(\text{syst})\ \text{pb}$$
$$\sigma_{\mathrm{t\bar{t}W}} = 0.77^{+0.12}_{-0.11}\,(\text{stat})^{+0.13}_{-0.12}\,(\text{syst})\ \text{pb}$$



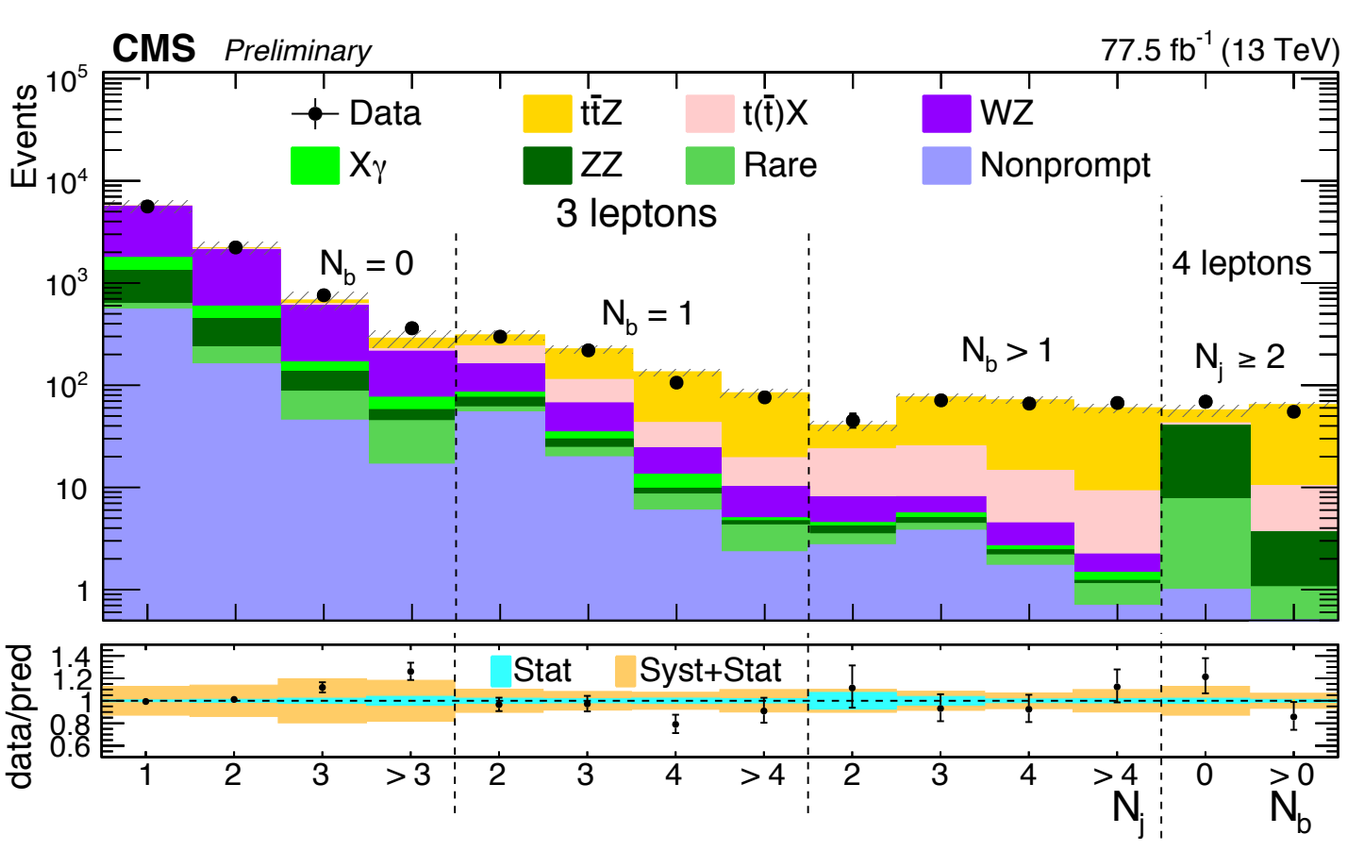
arXiv:1901.03584 (submitted to PRD)

2016/17 Dataset
77.5 fb^{-1}

ttZ CMS

New Result

- Measured in 3 or 4 lepton final states
  - Define signal regions based on jet/b-jet multiplicity
- In 2016 analysis, largest uncertainties:
  - Lepton ID efficiency, 6-7%
  - Trigger 5%
  - B-tagging uncertainties 4-5%
- Improved precision w.r.t. 2016 only analysis
  - More inclusive trigger
  - Lepton selection (BDT lepton ID)
  - Improved measurements of lepton and b-tagging efficiency



Source	Uncertainty range (%)	Impact on the tt̄Z cross section (%)
Trigger	2	2
Lepton ID efficiency	4.5–6	4
B tagging light flavor	0–4	1
B tagging heavy flavor	1–4	2

CMS PAS TOP-18-009

2016/17 Dataset
77.5 fb^{-1}

ttZ CMS

New Result

- Fit to event yields in jet/b-jet regions

Fit configuration	Measured signal strength
3ℓ	$1.24\ ^{+0.07}_{-0.07}(\text{stat})\ ^{+0.08}_{-0.08}(\text{syst})$
4ℓ	$1.15\ ^{+0.18}_{-0.17}(\text{stat})\ ^{+0.10}_{-0.08}(\text{syst})$
Combined	$1.19\ ^{+0.07}_{-0.06}(\text{stat})\ ^{+0.08}_{-0.07}(\text{syst})$

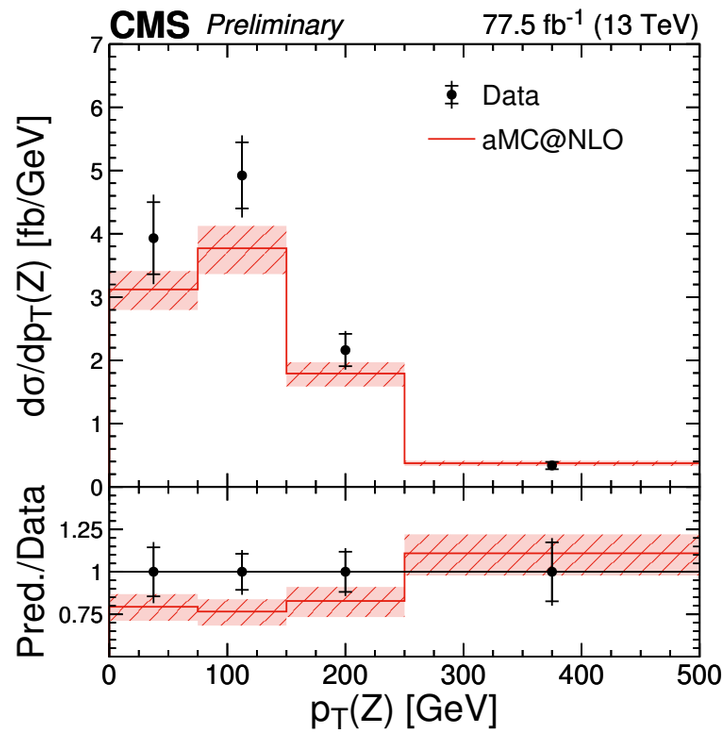
$$\sigma(pp \to t\bar{t}Z) = 1.00\ ^{+0.06}_{-0.05}(\text{stat})\ ^{+0.07}_{-0.06}(\text{syst})\ \text{pb}$$

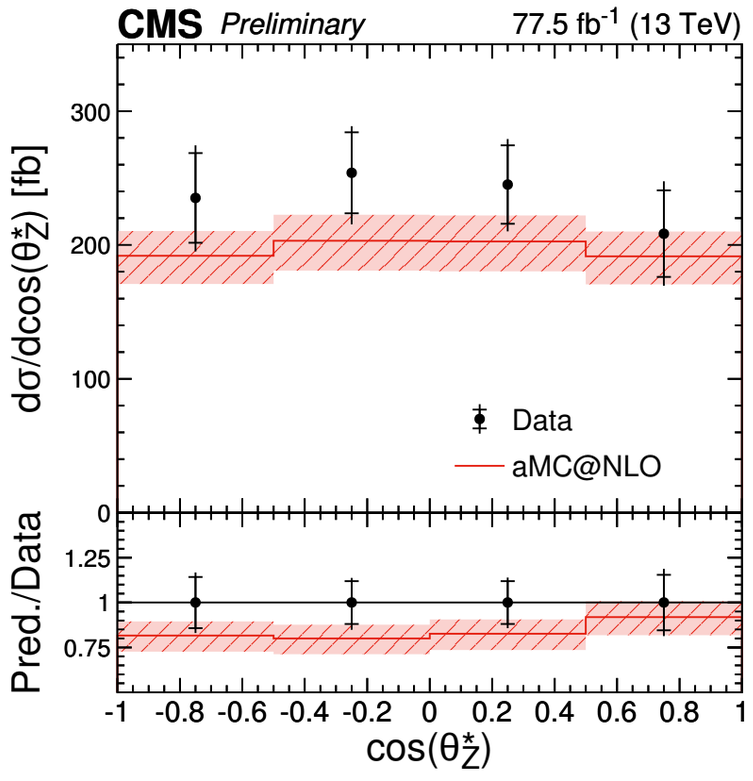
- Leading systematic uncertainties:
  - Lepton ID (4%)
  - t(t)X backgrounds (3%)
  - WZ cross section (3%)

- First measurement of differential distributions in ttZ process
  - Measured in 3ℓ, ≥3 jet, ≥1 b-jet final state

CMS PAS TOP-18-009

First Differential Measurements





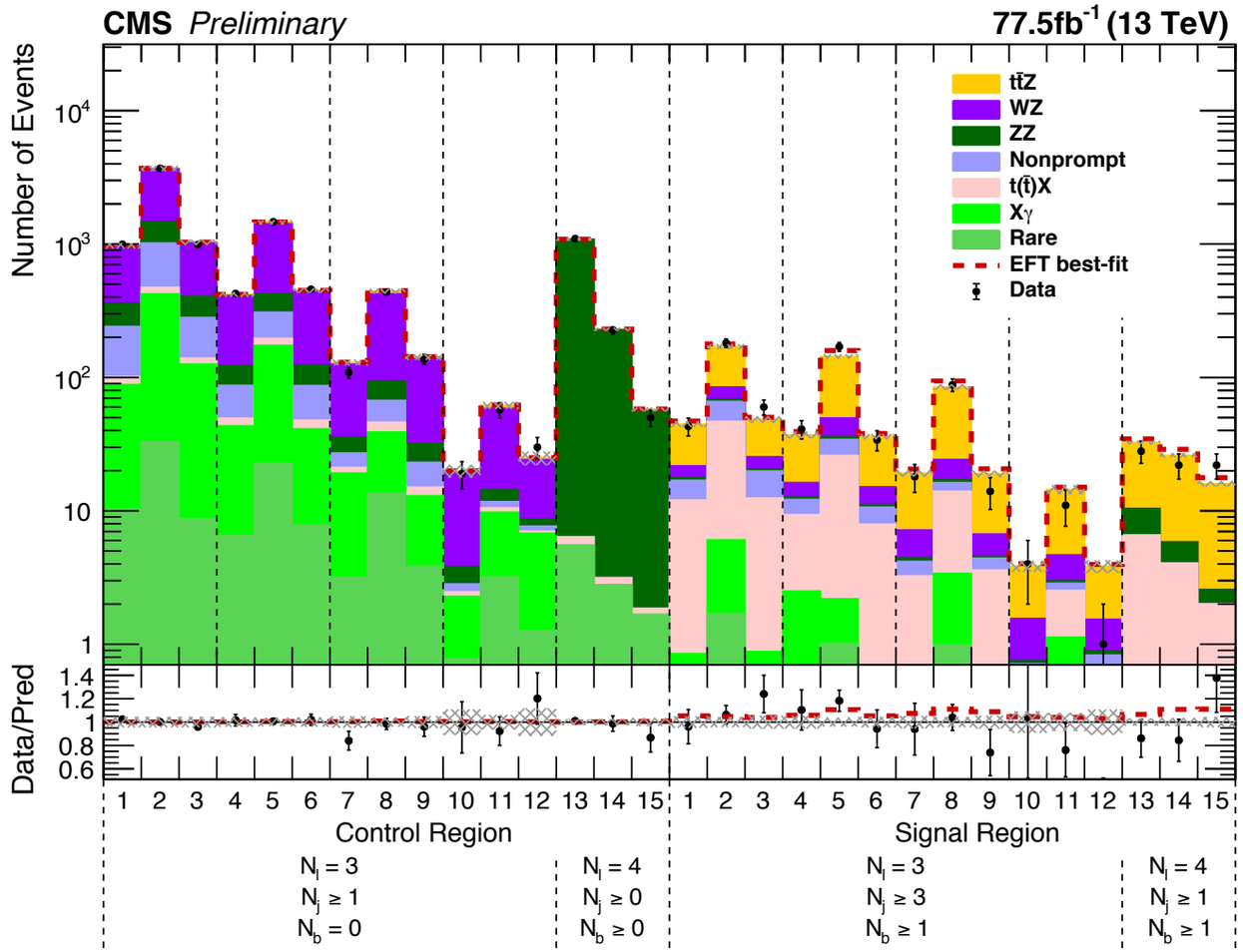
2016/17 Dataset
77.5 fb^{-1}

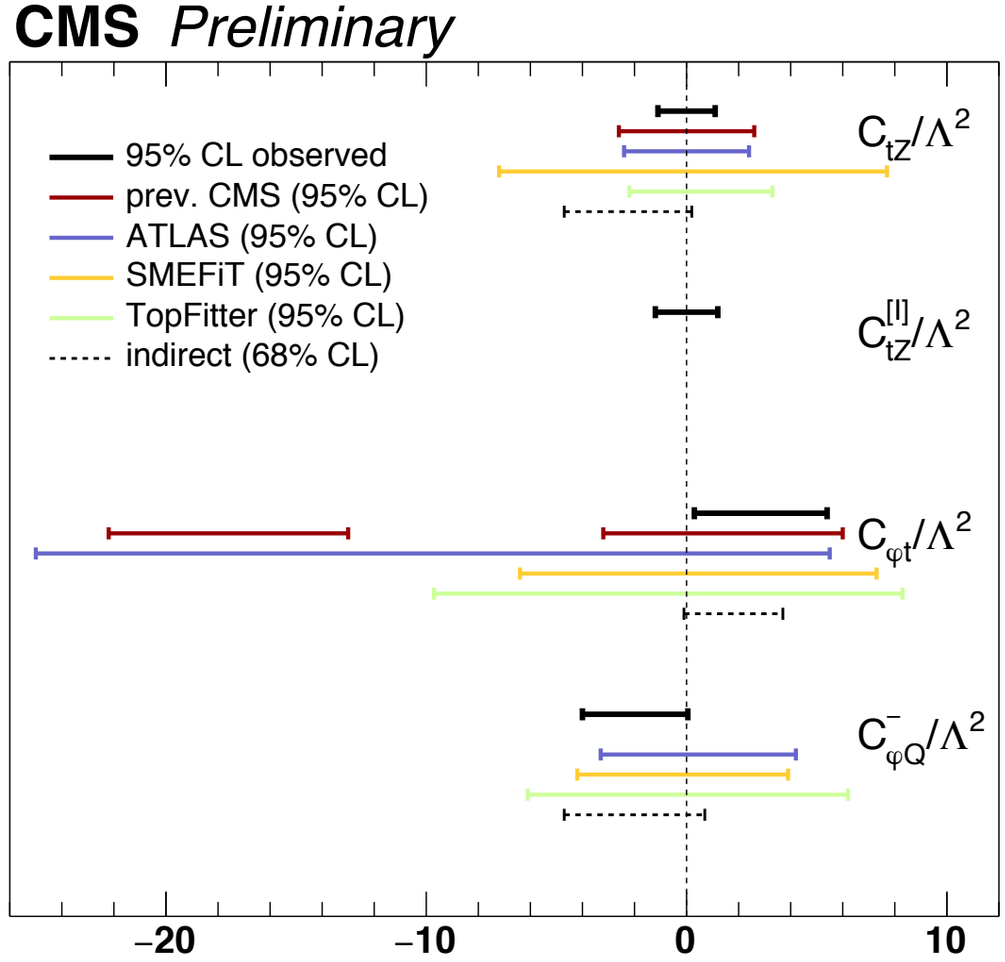
ttZ CMS

New Result

- Analysis can be used to set limits on SM EFT
  - Signal regions defined in bins of $p_T(Z)$, cos(θ*), and lepton/jet/b-jet multiplicity
- Parameterized in terms of coefficients on dim-6 operators having an impact on ttZ production [1]
- Fit to event yields in signal/control regions, floating operator coefficients in the fit

$$c_{tZ} = \mathrm{Re}\left(-\sin\theta_{\mathrm{W}} C_{\mathrm{uB}}^{(33)} + \cos\theta_{\mathrm{W}} C_{\mathrm{uW}}^{(33)}\right)$$
$$c_{tZ}^{[I]} = \mathrm{Im}\left(-\sin\theta_{\mathrm{W}} C_{\mathrm{uB}}^{(33)} + \cos\theta_{\mathrm{W}} C_{\mathrm{uW}}^{(33)}\right)$$
$$C_{\phi\mathrm{t}} = C_{\phi\mathrm{t}} = C_{\phi\mathrm{u}}^{(33)}$$
$$C_{\phi\mathrm{Q}}^{-} = C_{\phi\mathrm{Q}} = C_{\phi\{textq}^{1(33)} - C_{\phi\mathrm{q}}^{3(33)}$$





CMS PAS TOP-18-009

[1] arXiv:1802.07237

2015/16 Dataset
36.1 fb^{-1}

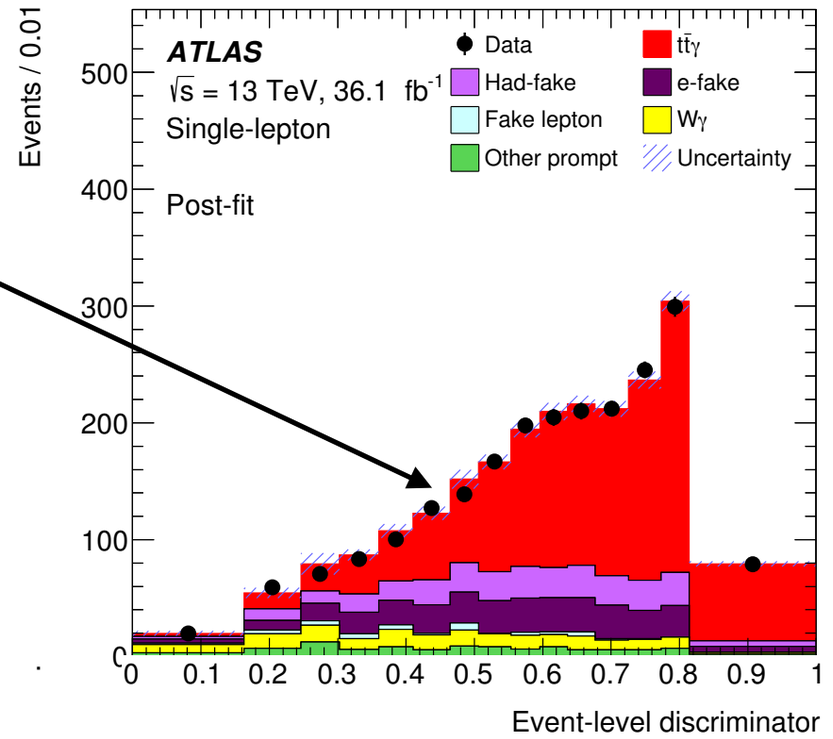
ttγ ATLAS

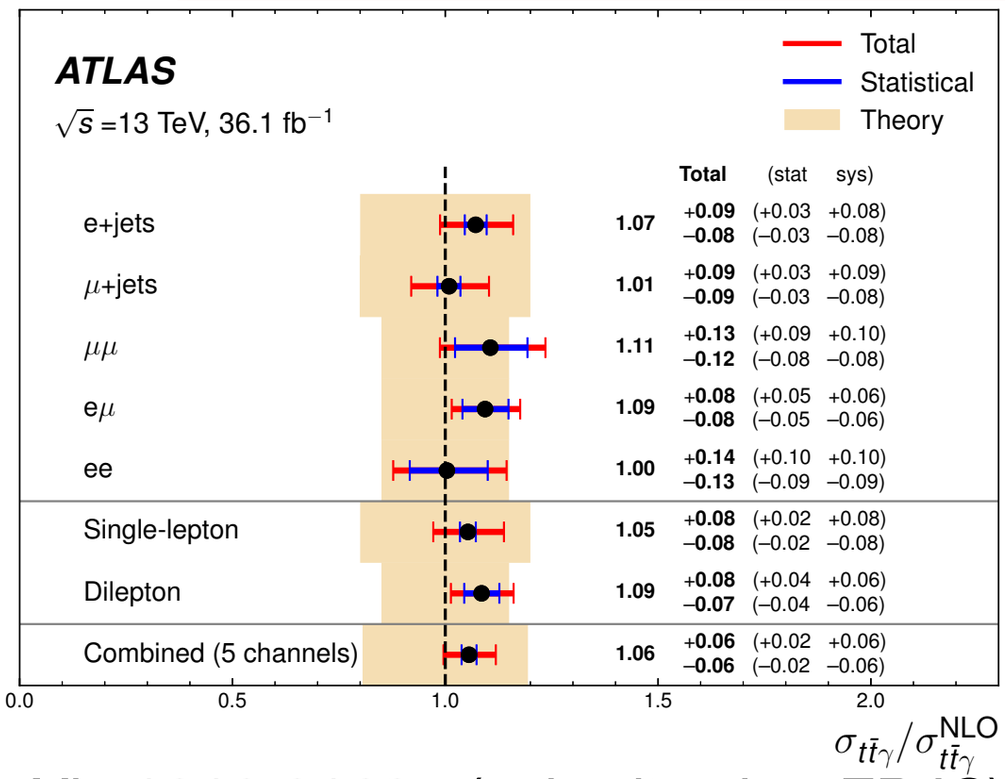
- Measurement in single-lepton and dilepton final states
  - W/Z +γ, fake photons, & misidentified electron backgrounds
- Two neural network algorithms trained in this analysis
  - Prompt-photon tagger to distinguish prompt and fake photons
  - Fit to **Event-level discriminant** distinguish signal/background
    - Inputs: jet p_T's, prompt-photon tagger output, b-tagging, etc.
- Systematics dominated by prompt-photon tagger and jet energy

Fiducial Cross section

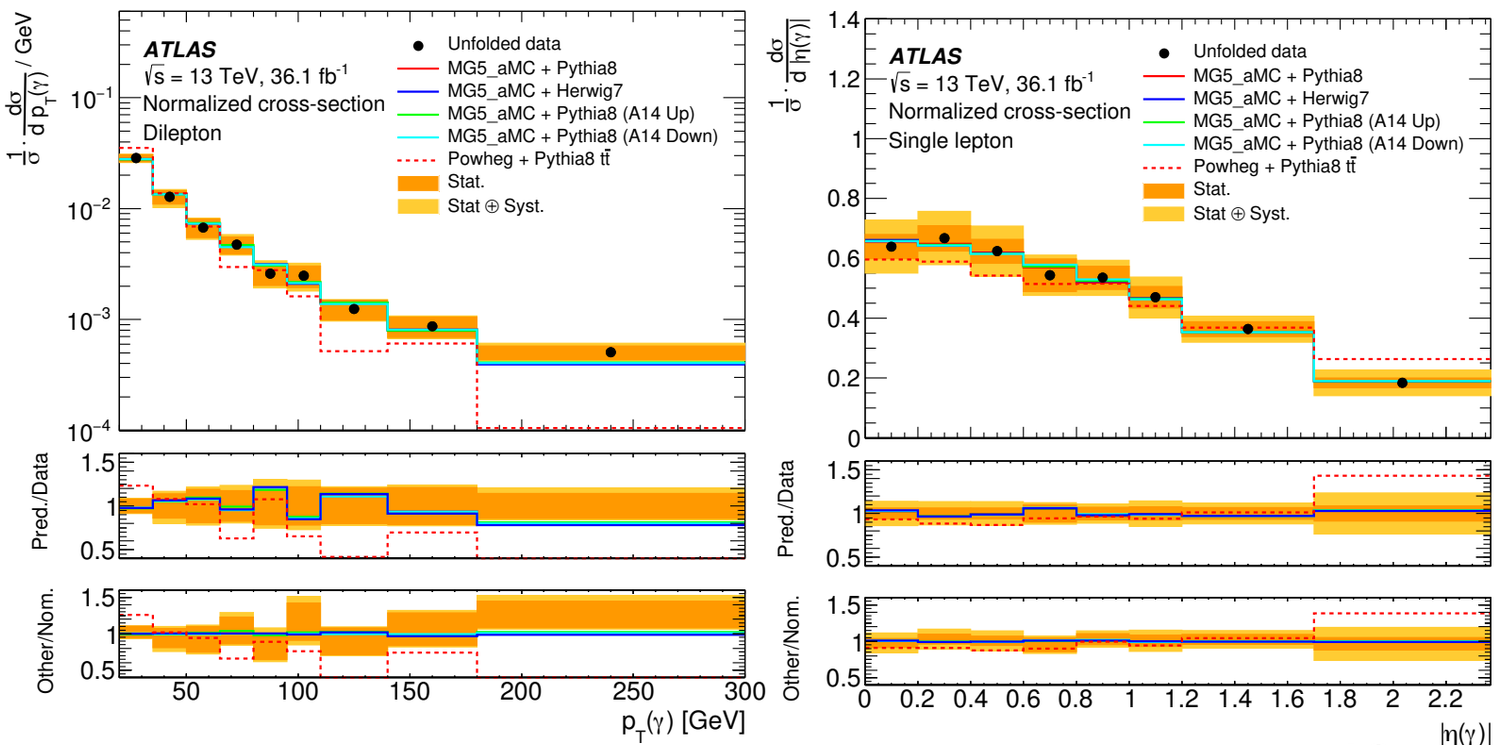
$$\sigma^{\text{fid.}}_{\ell+\text{jets}} = 521 \pm 9\ (\text{stat.}) \pm 41\ (\text{sys.})\ \text{fb}$$
$$\sigma^{\text{fid.}}_{\ell\ell} = 69 \pm 3\ (\text{stat.}) \pm 4\ (\text{sys.})\ \text{fb}$$

$\sigma^{\text{NLO}}_{\ell+\text{jets}} = 495 \pm 99$ fb [1] and $\sigma^{\text{NLO}}_{\ell\ell} = 63 \pm 9$ fb [1]





Differential Measurement

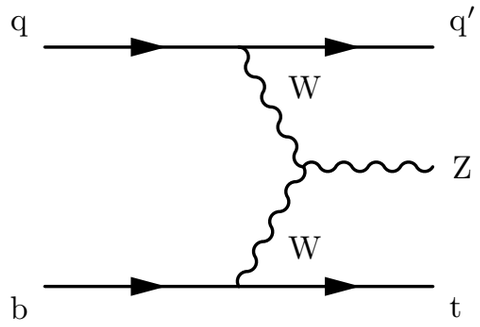


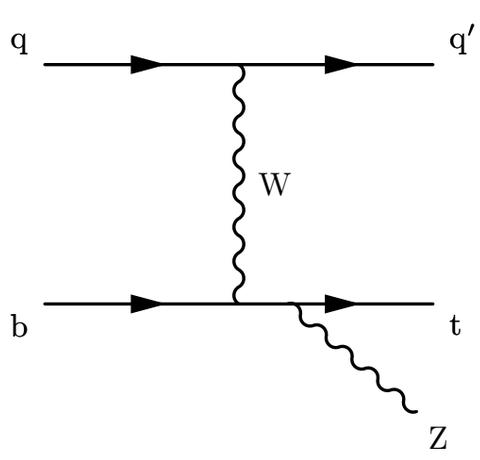
arXiv:1812.01697 (submitted to EPJC)

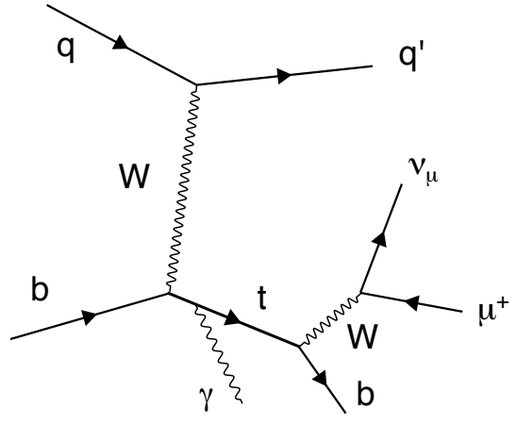
[1] Phys. Rev. D **83** (2011) 074013

Single top quark associated production

- Measurements of standard model associated production of single top quarks
  - tZq
  - tγ
- Rare production mechanisms that are within the reach of the LHC



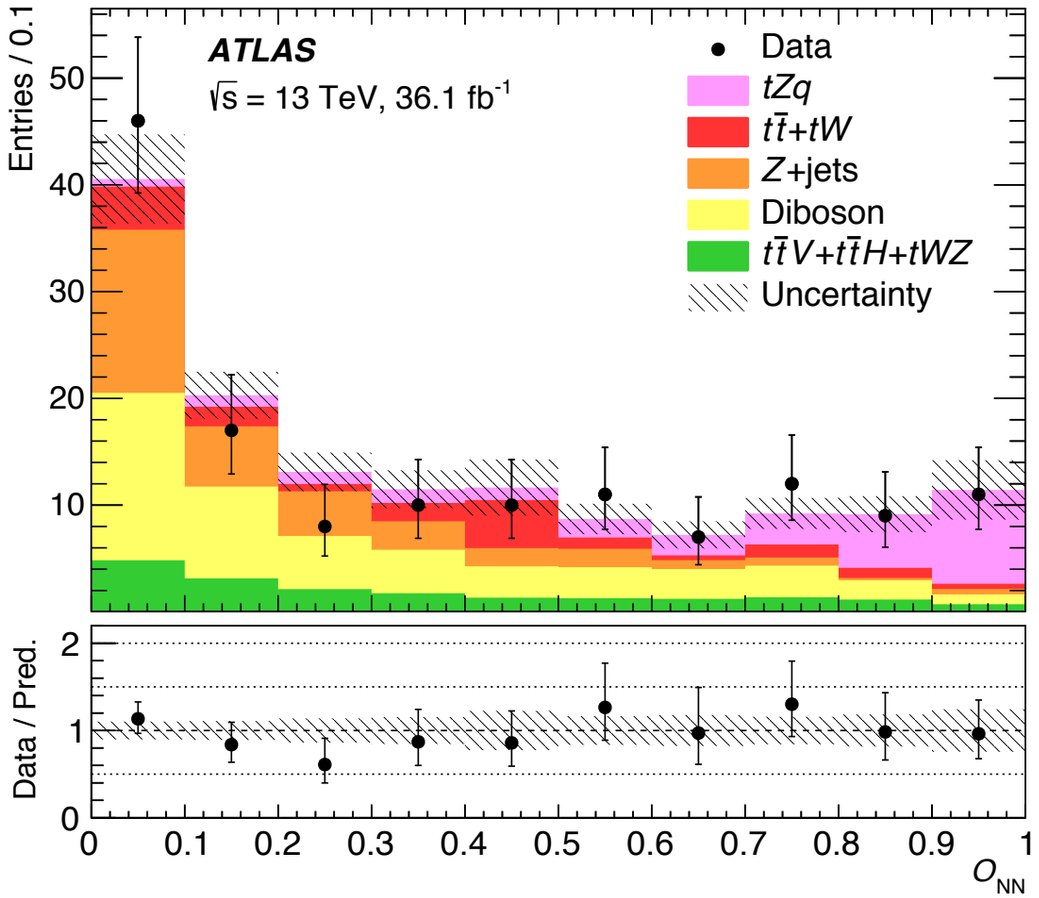




2015/16 Dataset
36.1 fb^{-1}

Evidence for tZq ATLAS

- Measurement in the 3 lepton final state, with one OS SF pair
  - Dominant backgrounds from tt, Z+jets, Diboson
- Fit to neural net discriminant
  - Inputs: p_T and η of the untagged jet, m_t^{reco}, $p_{T,\ell}$ from W boson, …
- Largest systematic uncertainties from modeling of additional radiation in signal sample



$$\sigma_{tZq} = 600 \pm 170(\text{stat.}) \pm 140(\text{syst.})\ \text{fb}$$

$$\sigma_{tZq}^{\text{NLO}} = 800\ \text{fb}^{+6.1\%}_{-7.4\%}\ [1]$$

4.2σ observed
5.4σ expected

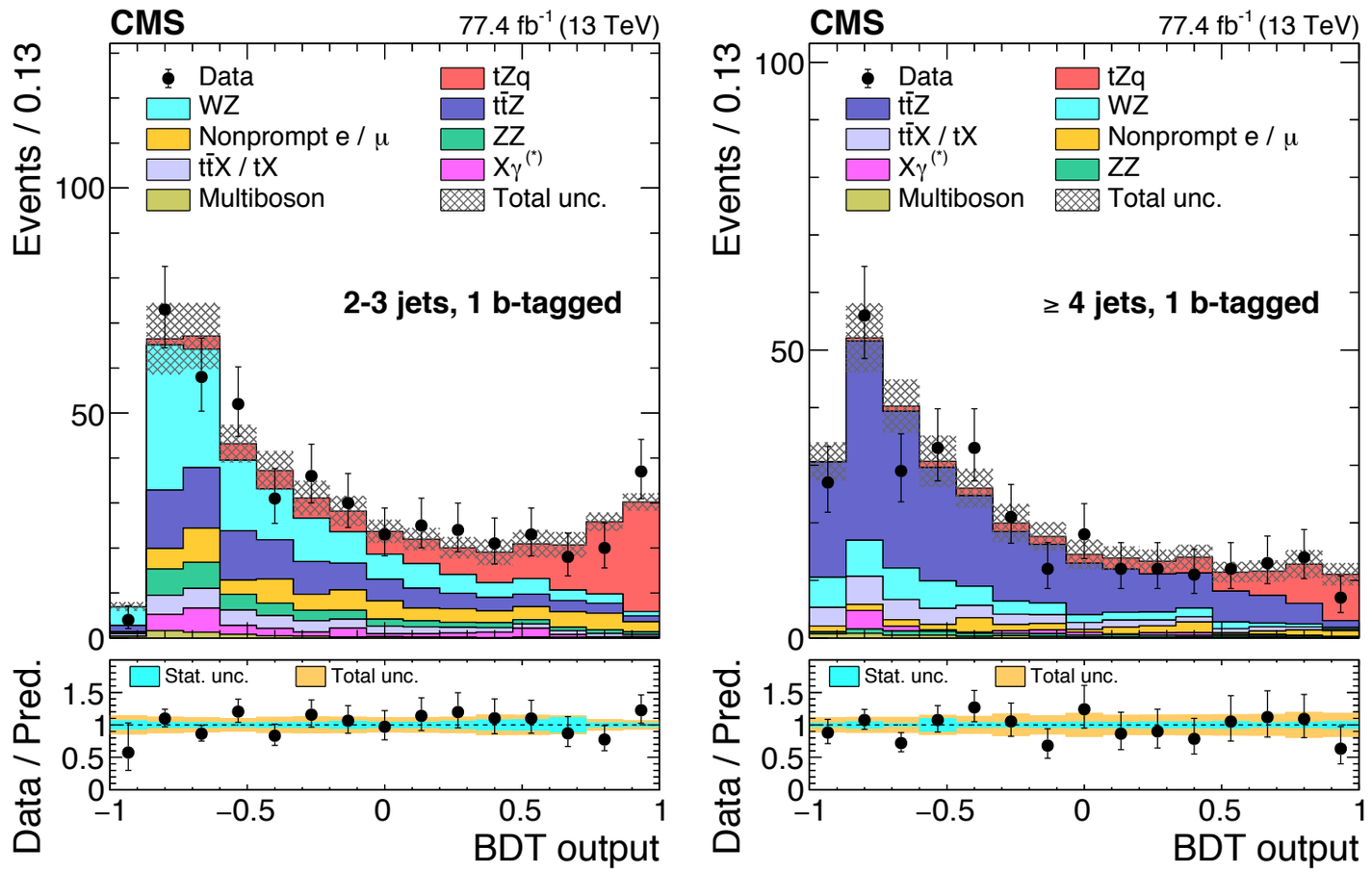
Phys. Lett. B 780 (2018) 557 (arXiv:1710.03659)

[1] J. High Energ. Phys. (2014) 2014: 79

2016/17 Dataset
77.4 fb^{-1}

Observation of tZq CMS

- Measurement in the 3 lepton final state
- BDT trained on signal and backgrounds in each signal region
  - eg:|η| of recoiling jet, max m_{jj}, W transverse mass
- Largest systematic uncertainties from:
  - Nonprompt background modeling
  - Lepton selection efficiency
  - Final state radiation
  - Jet energy



$$\sigma\ (pp \to tZq \to t\ell^+\ell^- q) = 111 \pm 13(\text{stat})^{+11}_{-9}(\text{syst})\ \text{fb}$$
$$\sigma^{\text{NLO}}(pp \to tZq \to t\ell^+\ell^- q) = 94.2 \pm 3.1\ \text{fb}^{[1]}$$
$$\text{Observed significance} > 5\sigma$$

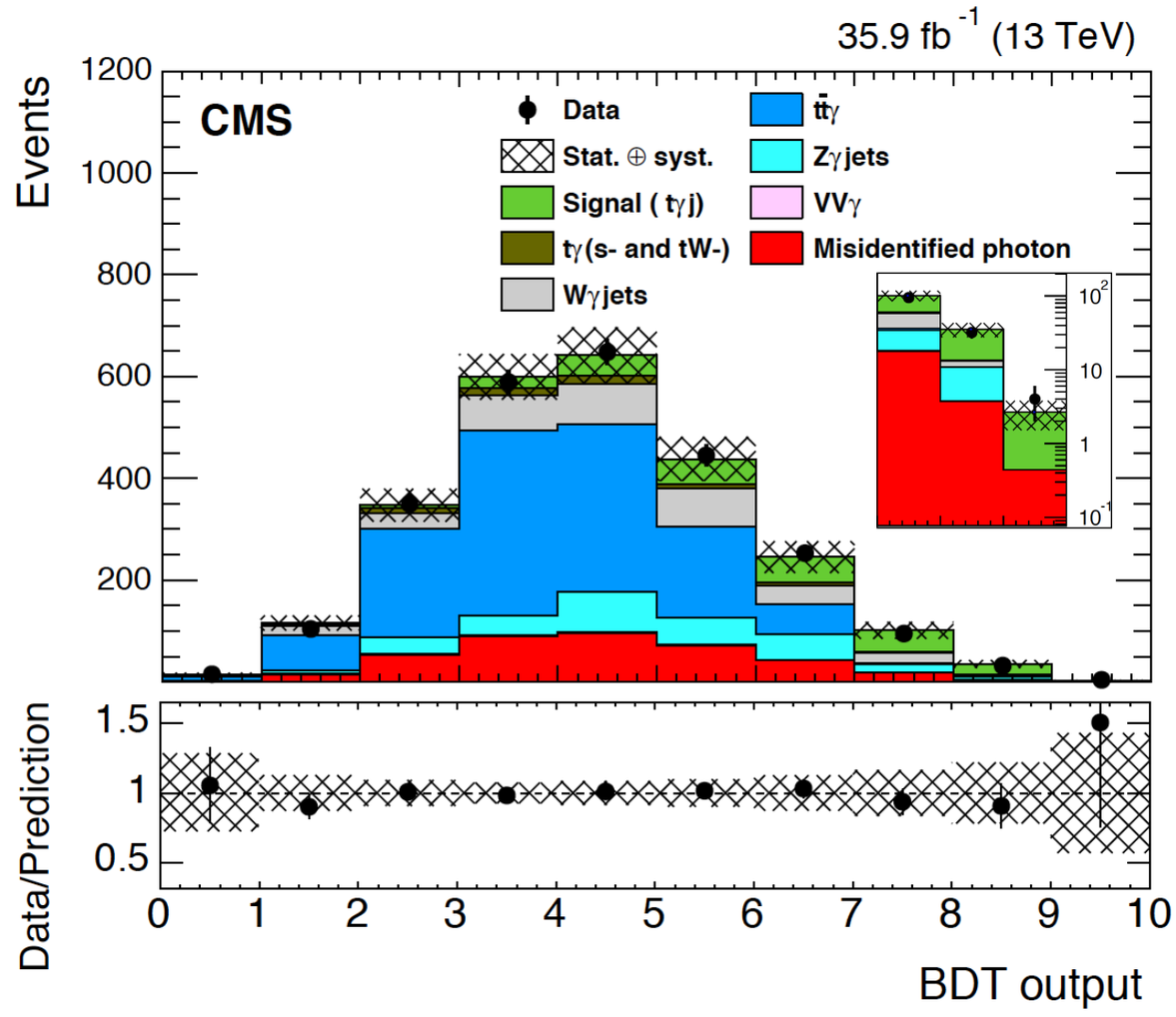
arXiv:1812.05900 (accepted by PRL)

[1] J. High Energ. Phys. (2014) 2014: 79

2016 Dataset
35.9 fb^{-1}

Evidence of tγ CMS

- Measured in the μ+jets final state
- BDT trained to discriminate signal from backgrounds
  - Inputs of η of light jet, cosθ, η of muon, …
- Limited by systematic uncertainties on jet energies, signal modeling, Zγ normalization, and b-tagging uncertainties



$$\sigma(pp \to t\gamma j)B(t \to \mu\nu b) = 115 \pm 17(\text{stat}) \pm 30(\text{syst})\ \text{fb}$$

$$\sigma_{\text{th}}^{\text{fid.}} = 81 \pm 4\text{fb} \qquad 4.4\sigma \text{ obs. } (3.0\sigma \text{ exp.})$$

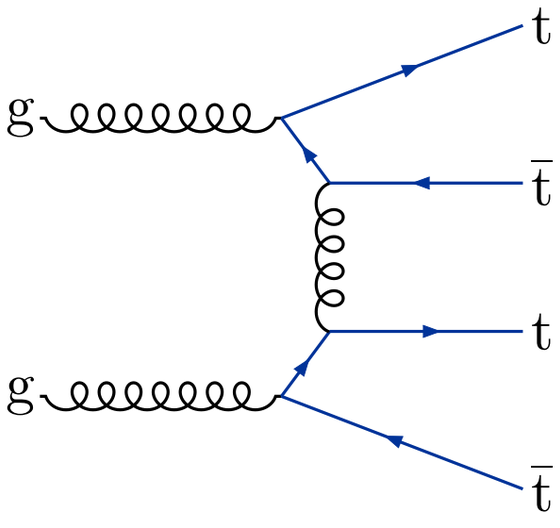
Phys. Rev. Lett. 121 (2018) 221802 (arXiv:1808.02913)

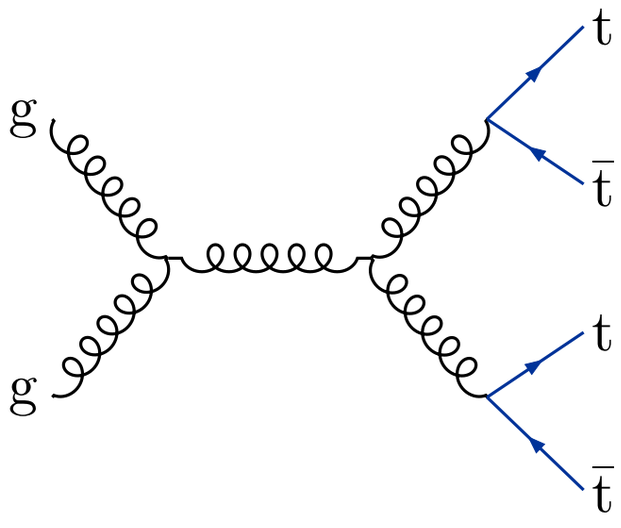
Four top production

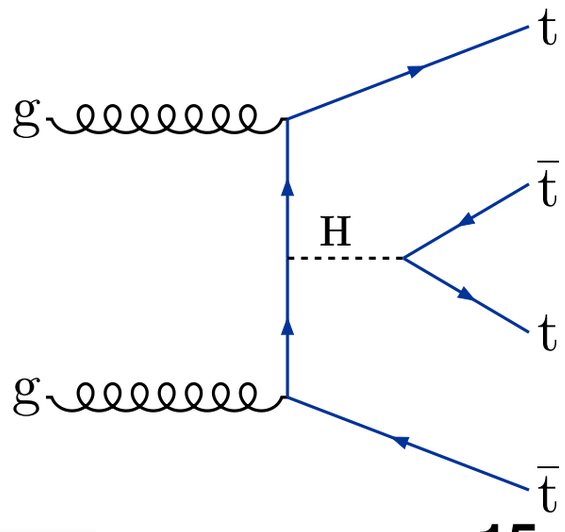
- Rare production mechanism in the SM

$$\sigma^{\mathrm{SM}}_{\mathrm{t\bar{t}t\bar{t}}} = 9.2^{+2.9}_{-2.4}\ \mathrm{fb}^{[1]}\ \mathrm{at\ NLO}$$

- Can receive significant enhancements in BSM models
- Analyses split by leptonic final state:
  - SS dilepton and multilepton (≥3)
  - Single lepton and OS dilepton





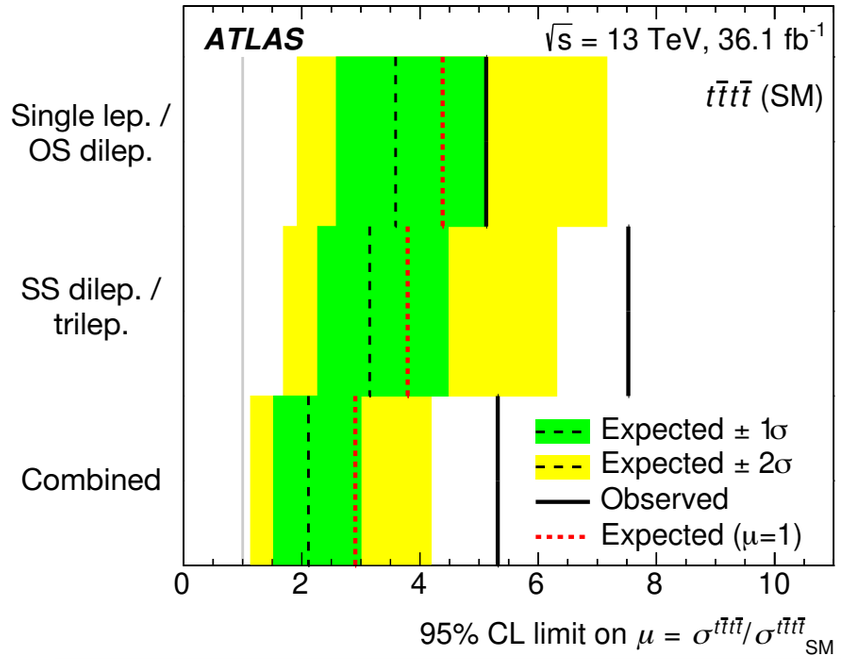


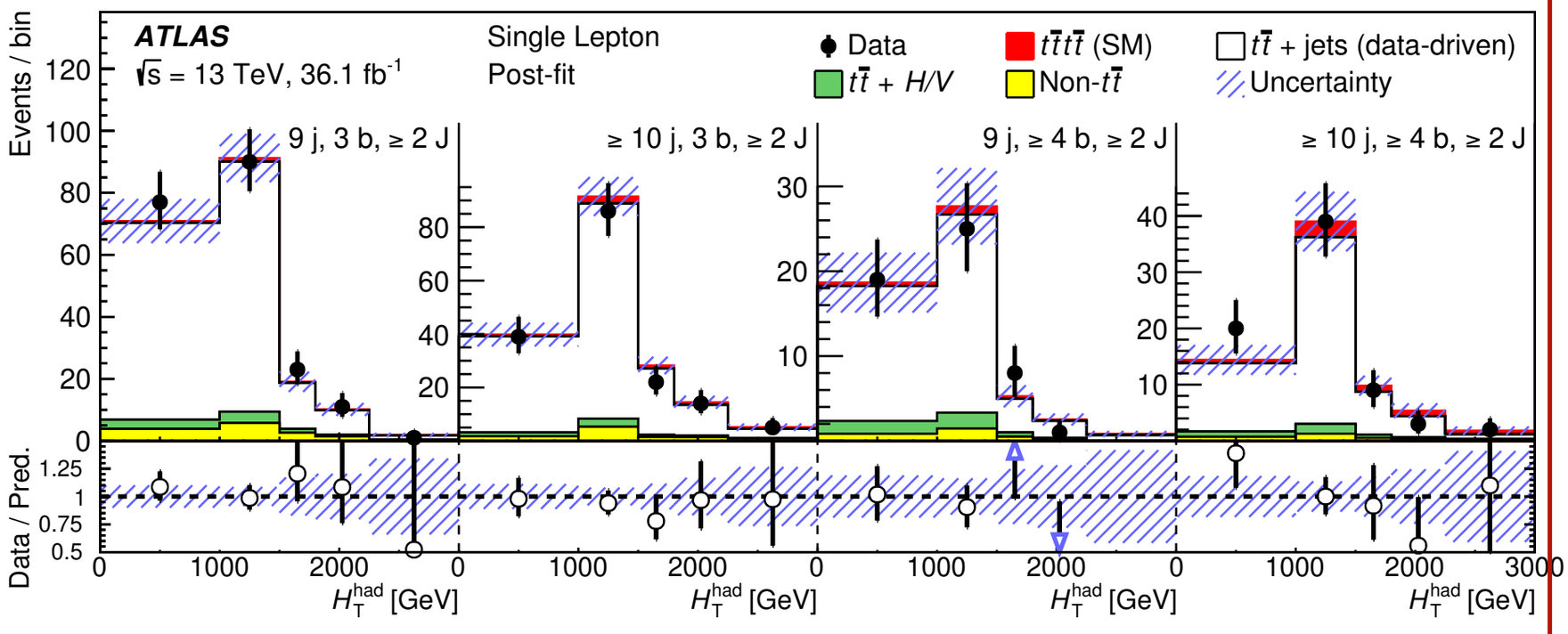
[1] J. High Energ. Phys. (2014) 2014: 79

2015/16 Dataset
36.1 fb^{-1}

Four top ATLAS

- Analysis in single-lepton and OS dilepton final states
  - Dominant background from top pair production
- Fit to scalar sum of jet p_T (H_T^{had}) in signal regions (defined by jet/b-jet/large-R jet multiplicities)
- Combined with previous measurement in the SS dilepton and multilepton final states[1]





This analysis

Best fit $\mu = 1.7^{+1.9}_{-1.7}$

95% CL upper limit 47 fb

Combined with SS 2ℓ and 3ℓ [1]

Best fit $\mu = 3.1^{+1.3}_{-1.2}$

95% CL upper limit 49 fb

Limit on EFT 4 top contact interaction

$|C_{4t}|/\Lambda^2 < 1.9\ \text{TeV}^{-2}$

arXiv:1811.02305, submitted to Phys. Rev. D

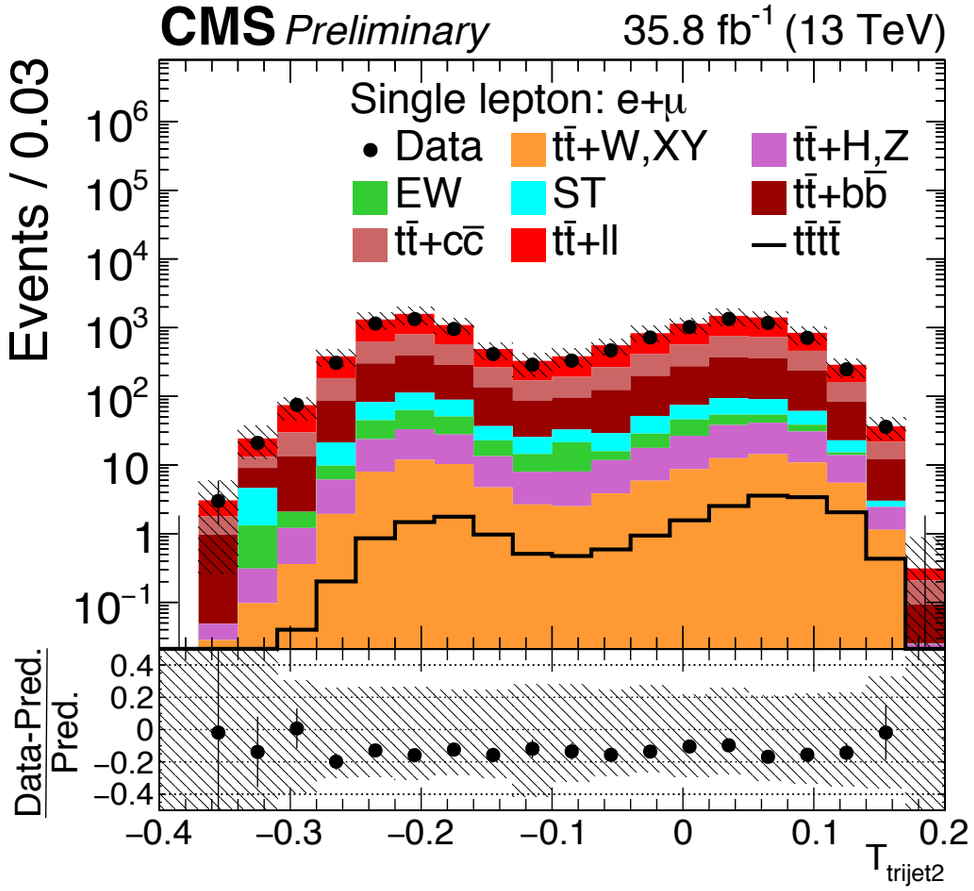
[1] JHEP 07 (2018) 089 (arXiv:1803.09678)

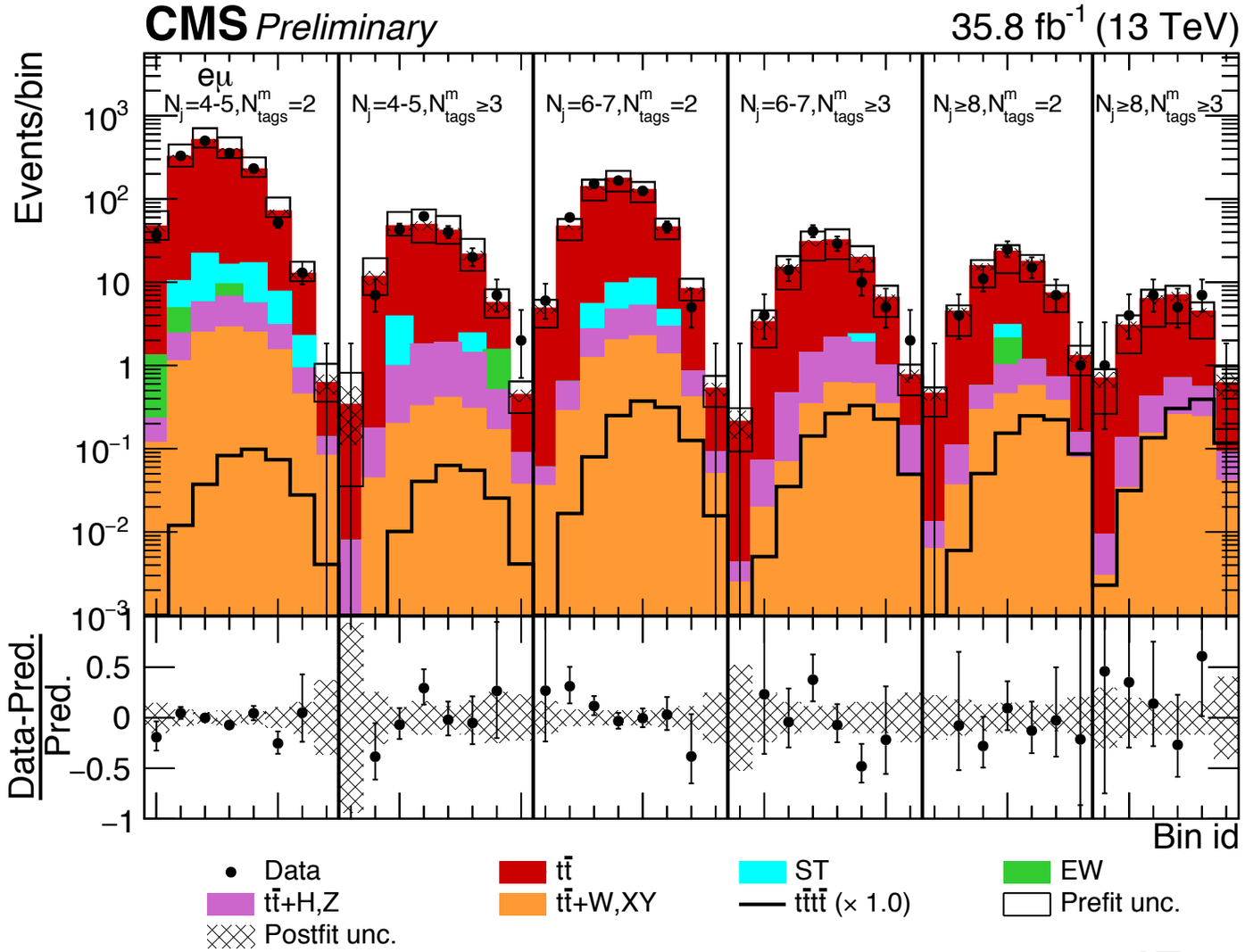
2016 Dataset
35.8 fb^{-1}

Four top CMS

New Result

- Measurement in the single-lepton and OS dilepton final states
- Identify trijet combinations likely coming from hadronically decaying top quarks with BDT (T_{trijet})
- Separate BDT's trained in lepton final states and jet/b-jet multiplicity bins to separate four top from top pair background





CMS PAS TOP-17-019

2016 Dataset
35.8 fb^{-1}

Four top CMS

New Result

- Simultaneous fit to BDT discriminants
- Dominant systematic uncertainties from modeling of top pair background
- Combined with previous measurement in SS dilepton and multilepton final states[1]
- One of the best limits to date for SM four top production

Channel	Best-fit μ	Obs (Exp) upper limit
Single lepton	$1.6^{+4.6}_{-1.6}$	97 (86) fb
Dilepton	$0.0^{+2.7}$	64 (67) fb
Combined	$0.0^{+2.2}$	48 (52) fb
Multilepton[1]	$1.8^{+1.5}_{-1.2}$	42 (23) fb
Combined	$1.4^{+1.2}_{-1.0}$	33 (20) fb

Operator	Expected C_k/Λ^2 (TeV^{-2})	Observed C_k/Λ^2(TeV^{-2})
$\mathcal{O}^1_{tt}$	$[-1.5, 1.3]$	$[-2.1, 2.0]$
$\mathcal{O}^1_{QQ}$	$[-1.5, 1.3]$	$[-2.2, 2.0]$
$\mathcal{O}^1_{Qt}$	$[-2.4, 2.4]$	$[-3.5, 3.5]$
$\mathcal{O}^8_{Qt}$	$[-5.6, 4.3]$	$[-7.9, 6.6]$

- Can be interpreted in terms of EFT limits
  - Considering coefficients on dim-6 operators effecting four top cross section

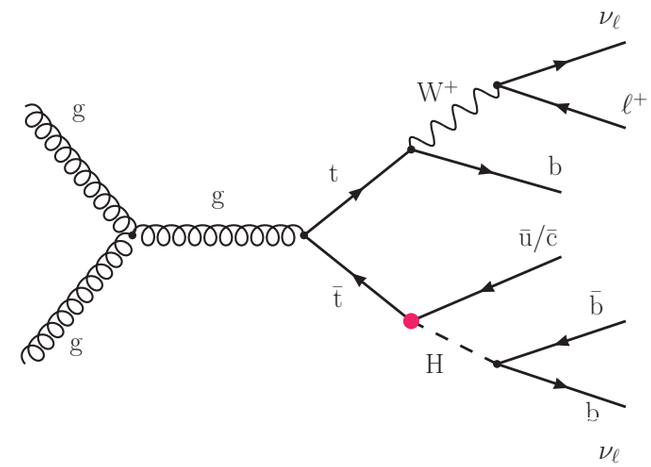
CMS PAS TOP-17-019

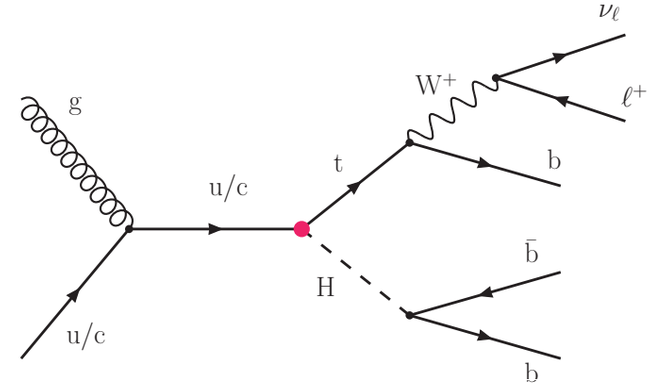
[1] Eur. Phys. J. C 78 (2018) 140 (arXiv:1710.10614)

Searches for Flavor Changing Neutral Currents

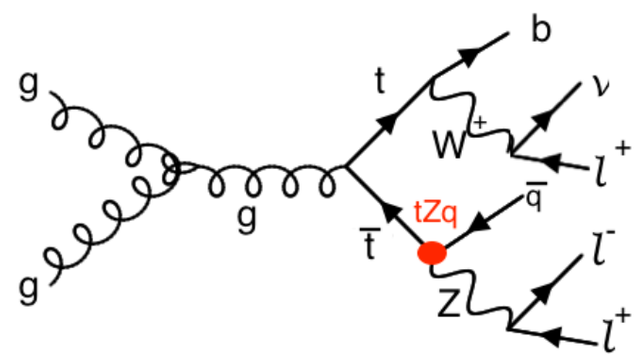
- In the SM, top decays almost exclusively to W boson and b quark
- Flavor changing neutral current (FCNC) decays forbidden at tree level and strongly suppressed at higher orders
- New physics models predict significant enhancements to this

Model:	SM	QS	2HDM	FC 2HDM	MSSM
$\mathcal{B}(t \to qZ)$:	10^{-14}	10^{-4}	10^{-6}	10^{-10}	10^{-7}





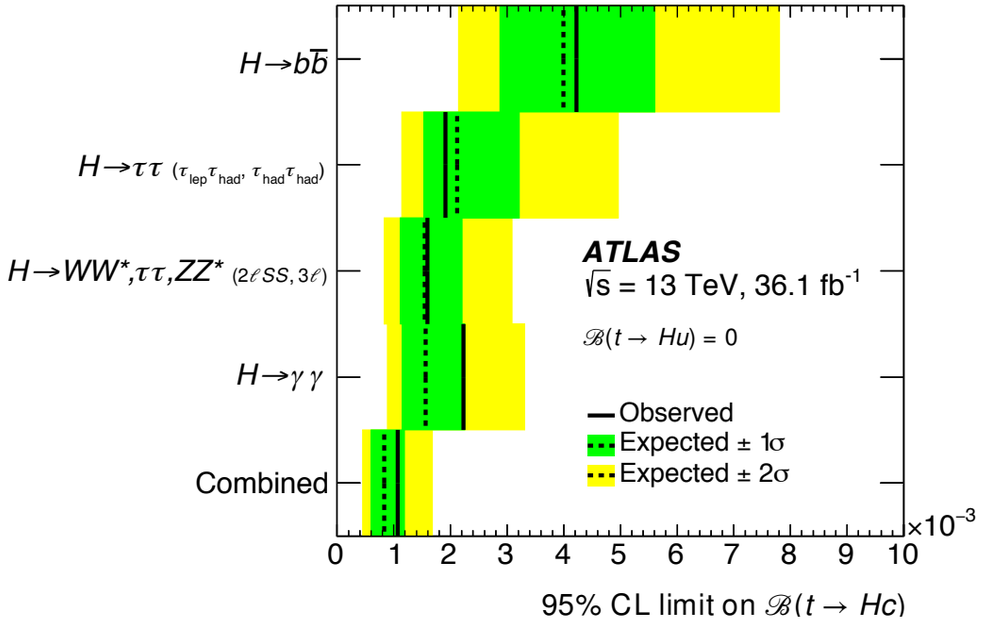
- Searches at the LHC looking for either pair production with a top decaying via a FCNC interaction, or single production via a FCNC vertex

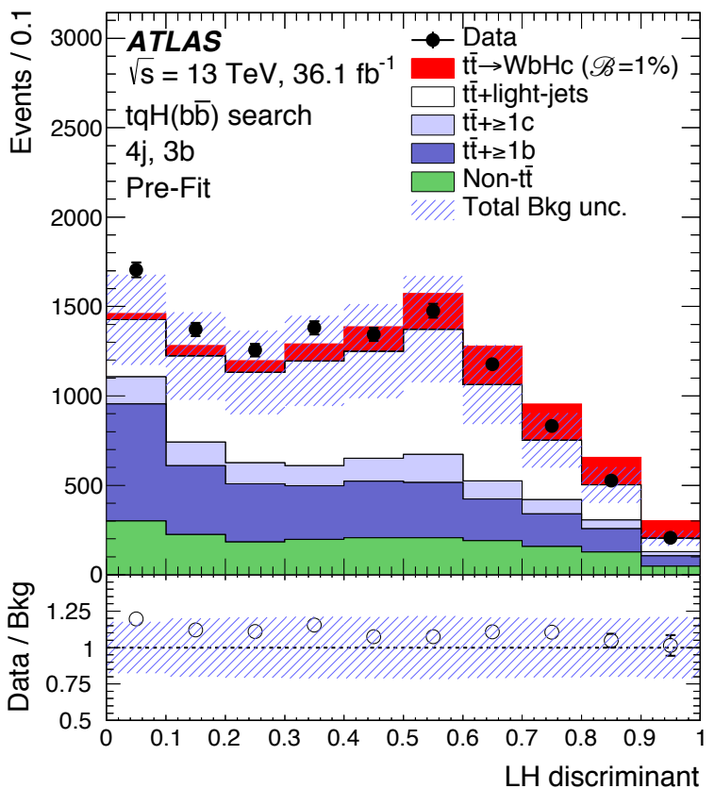


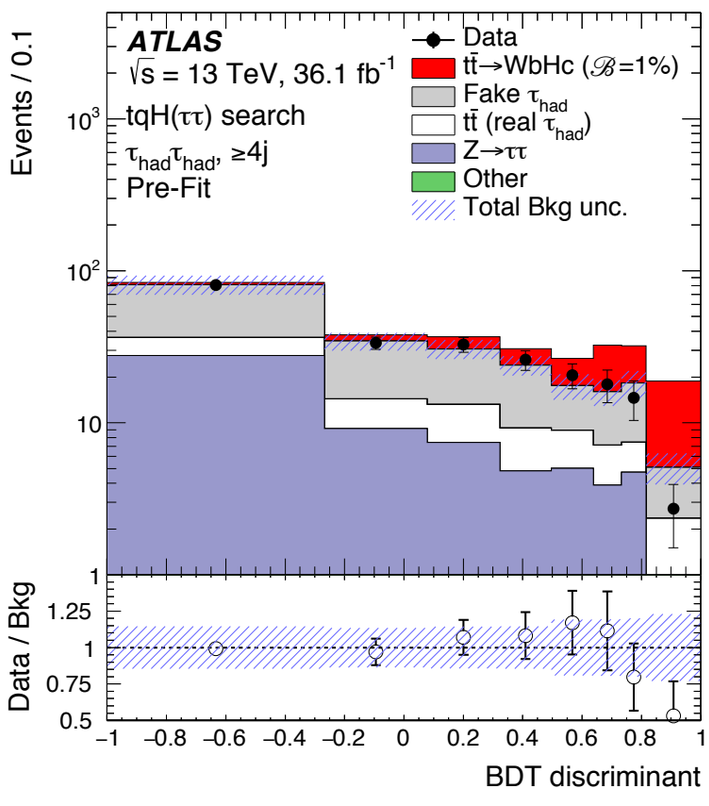
2015/16 Dataset
36.1 fb^{-1}

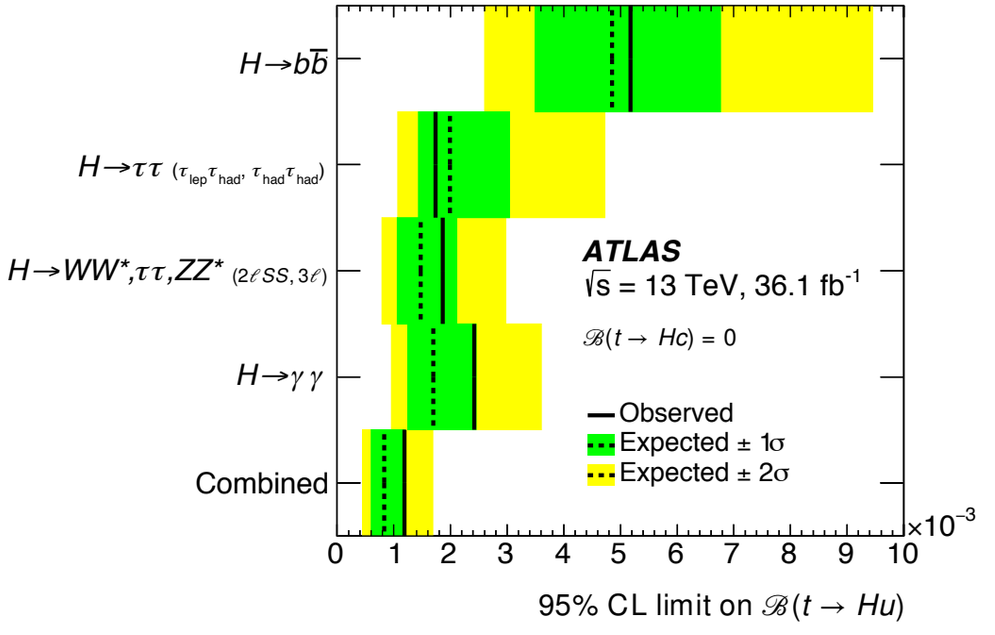
FCNC tHq ATLAS

- Search in top pair production, with one decaying t->Hu(c) in H->bb and H->$\tau\tau$ final states
- Dominant backgrounds from SM tt decays and fake τ
- Likelihood discriminant defined in H->bb final state
- BDT trained in H->$\tau\tau$ final states
- Combined with measurement in diphoton[1] and multilepton[2] final states









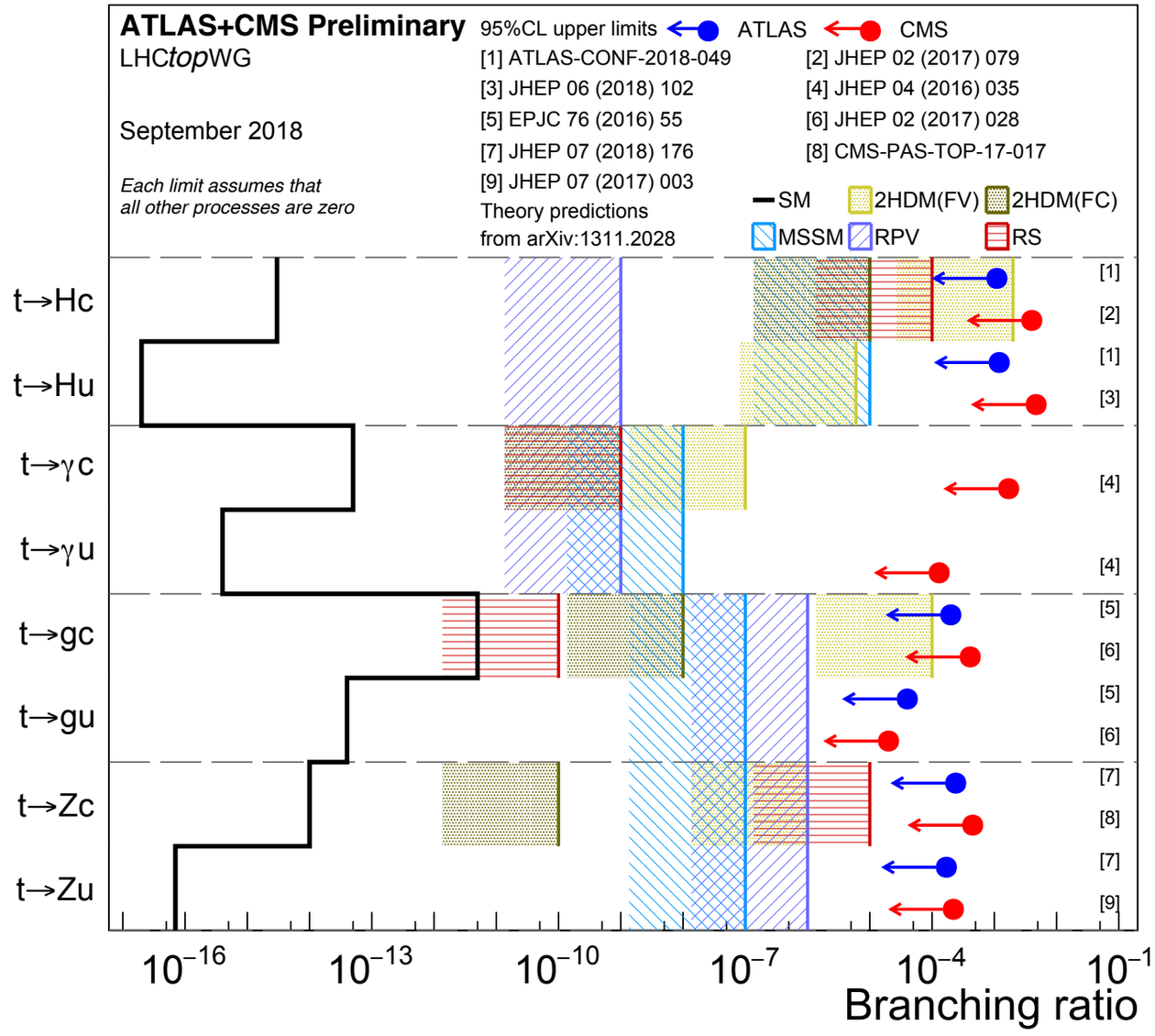
$$B(t \to Hc) < 1.1 \times 10^{-3} (8.3 \times 10^{-4})$$
$$B(t \to Hu) < 1.2 \times 10^{-3} (8.3 \times 10^{-4})$$

arXiv:1812.11568 submitted to JHEP

[1] JHEP 10 (2017) 129 (arXiv:1707.01404)
[2] Phys. Rev. D 98 (2018) 032002 (arXiv:1710.10614)

ATLAS & CMS FCNC Limits

- Limits placed in many top decay final states
  - t->Hq
  - t->γq
  - t->gq
  - t->Zq
- Upper limits are approaching sensitivity to BSM models



2016 Dataset
35.9 fb^{-1}

New Physics via top production

- Search in the dilepton final state for new physics
  - Measured in both tt and tW dilepton final states
- Split by jet/b-jet multiplicity
- Neural networks trained separately in jet/b-jet bins targeting FCNC operators $C_{u(c)G}$ and $C_{\phi q}^{(3)}$, C_{tW}, C_{tG}
- Event yields used to constrain C_G

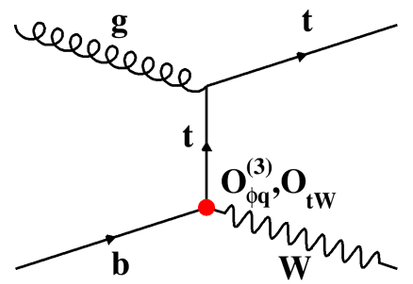
$$O_{\phi q}^{(3)} = (\phi^+ \tau^I D_\mu \phi)(\bar{q}\gamma^\mu \tau^I q),$$

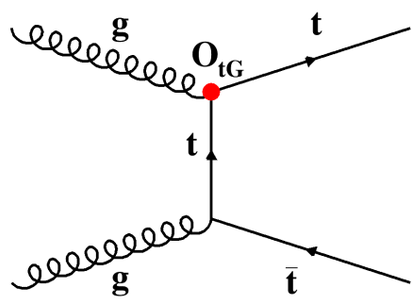
$$O_{tW} = (\bar{q}\sigma^{\mu\nu}\tau^I t)\tilde{\phi} W_{\mu\nu}^I,$$

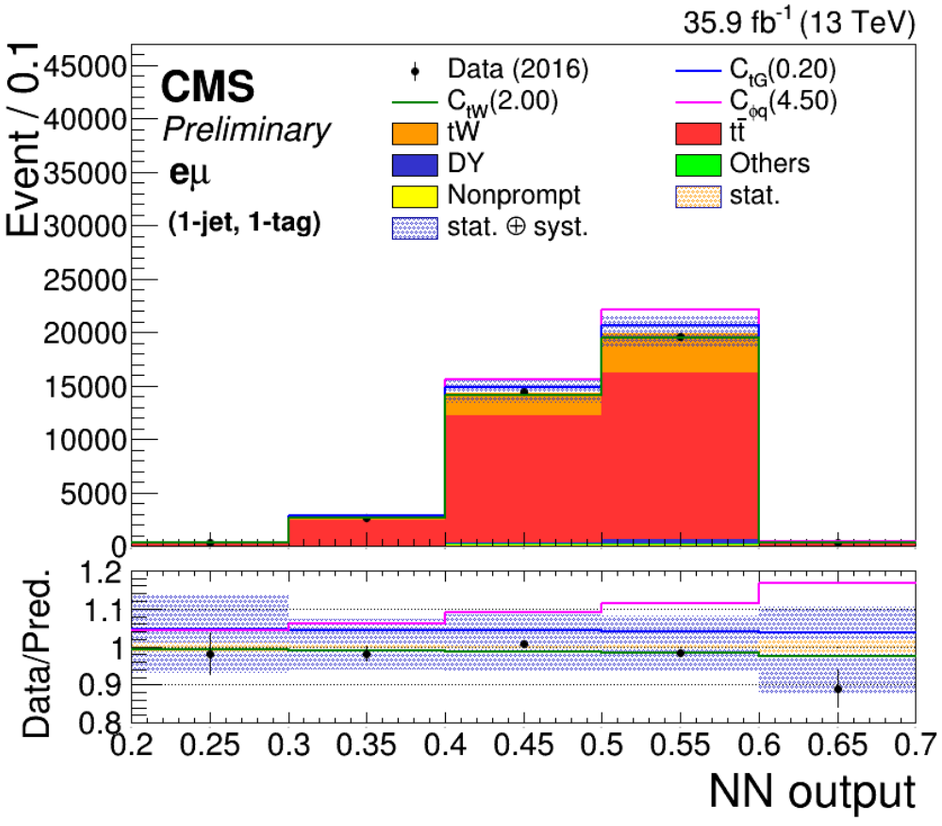
$$O_{tG} = (\bar{q}\sigma^{\mu\nu}\lambda^A t)\tilde{\phi} G_{\mu\nu}^A,$$

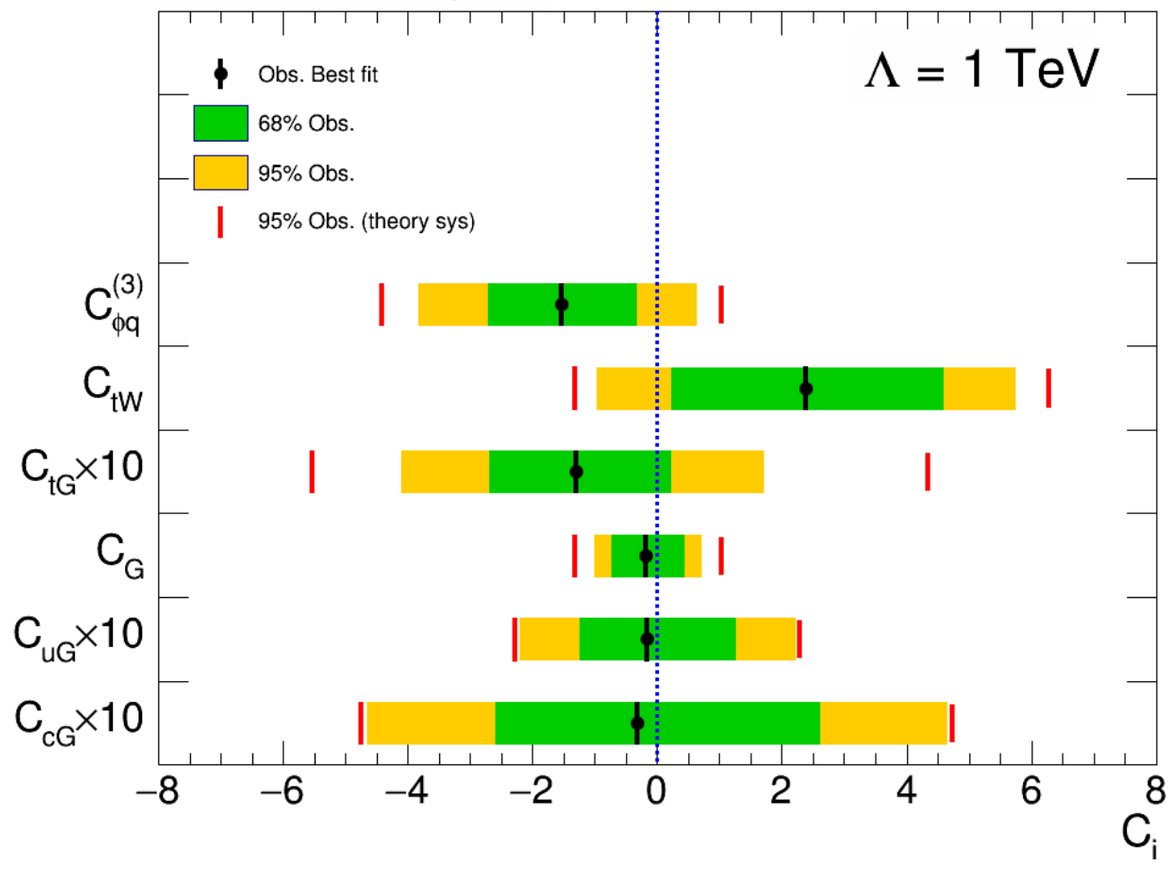
$$O_G = f_{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu},$$

$$O_{u(c)G} = (\bar{q}\sigma^{\mu\nu}\lambda^A t)\tilde{\phi} G_{\mu\nu}^A,$$









CMS PAS TOP-17-020

Summary

- Many measurements of rare top quark production mechanisms performed with data from Run 2 of the LHC
  - Good agreement with the SM predictions observed
- **Associated production** of single top or top pairs with electroweak bosons moving from searches to precision measurements
- **Four top production** approaching SM sensitivity
- Limits on **rare top decays** are approaching sensitivity to BSM models

Thank you for your attention!

Summary

- **ttW/ttZ**
  - **CMS** (ttW/ttZ): JHEP 08 (2018) 011 (arXiv:1711.02547)
  - **CMS** (ttZ) : CMS PAS TOP-18-009
  - **ATLAS** (ttW/ttZ) arXiv:1901.03584 (submitted to PRD)
- **tt+gamma**:
  - **ATLAS** arXiv:1812.01697 (submitted to EPJC)
- **tZq**:
  - **CMS** : arXiv:1812.05900 (accepted by PRL)
  - **ATLAS** : Phys. Lett. B 780 (2018) 557 (arXiv:1710.03659)
- **t+gamma**
  - **CMS** : Phys. Rev. Lett. 121 (2018) 221802 arXiv:1808.02913
- **4-top production**
  - **CMS** : (SS dilepton & multilepton) Eur. Phys. J. C 78 (2018) 140 (arXiv:1710.10614)
  - **CMS** : (OS dilepton & single lepton) CMS PAS TOP-17-019
  - **ATLAS** : (SS dilepton & multilepton) JHEP 07 (2018) 089 (arXiv:1803.09678)
  - **ATLAS** : (OS dilepton & single lepton) arXiv:1811.02305, submitted to Phys. Rev. D
- **FCNC**:
  - **CMS** : (t->Zq) CMS PAS TOP-17-017
  - **CMS** : (t->Hq) JHEP 06 (2018) 102 (arXiv:1712.02399)
  - **ATLAS** : (t -> Hq) arXiv:1812.11568 submitted to JHEP
  - **ATLAS** : (t -> Zq) JHEP 07 (2018) 176 (arXiv:1803.09923)
- **New Physics**:
  - **CMS** : New physics in dilepton events CMS PAS TOP-17-020
  - **ATLAS** : Lepton flavor violation in top decays ATLAS-CONF-2018-044

Link to CMS Top Results

Link to ATLAS Top Results

Backup

ttW : ATLAS

2 lepton SS Signal Region definitions in ttW analysis

Requirement	2ℓ-SS(p,m)-1b	$2e$-SS(p,m)-2b	$e\mu$-SS(p,m)-2b	2μ-SS(p,m)-2b
$n_{b\text{-tags}}$	$=1$	≥ 2	≥ 2	≥ 2
$E_{\mathrm{T}}^{\mathrm{miss}}$	> 40 GeV	> 40 GeV	> 40 GeV	> 20 GeV
H_{T}	> 240 GeV			
p_{T} (leading lepton)	> 27 GeV			
p_{T} (subleading lepton)	> 27 GeV			
n_{jets}	≥ 4	≥ 4	≥ 4	≥ 2
Z veto	$\lvert m_{\ell\ell} - m_Z \rvert > 10\,\mathrm{GeV}$ in the $2e$ and 2μ regions			

3 lepton Signal Region definitions in ttW analysis

Variable	3ℓp-noZ-2b2j	3ℓm-noZ-2b2j	3ℓp-noZ-1b2j	3ℓm-noZ-1b2j
All leptons	$p_{\mathrm{T}} > 27\,\mathrm{GeV}$			
Z veto (OSSF pair)	$\lvert m_{\ell\ell} - m_Z \rvert > 10\,\mathrm{GeV}$			
n_{jets}	2 or 3			
H_{T}	–		> 240 GeV	
Sum of lepton charges	$+1$	-1	$+1$	-1
$n_{b\text{-tags}}$	≥ 2	≥ 2	1	1

arXiv:1901.03584 (submitted to PRD)

ttZ ATLAS

2 lepton OS Signal Region definitions in ttZ analysis

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

3 lepton Signal Region definitions in ttZ analysis

Variable	3ℓ-Z-1b4j	3ℓ-Z-2b3j	3ℓ-Z-2b4j	3ℓ-noZ-2b4j
Leading lepton	$p_\text{T} > 27\,\text{GeV}$			
Other leptons	$p_\text{T} > 20\,\text{GeV}$			
Sum of lepton charges	± 1			
Z requirement (OSSF pair)	$\lvert m_{\ell\ell} - m_Z \rvert < 10\,\text{GeV}$		$\lvert m_{\ell\ell} - m_Z \rvert > 10\,\text{GeV}$	
n_jets	≥ 4	3	≥ 4	≥ 4
$n_{b\text{-tags}}$	1	≥ 2	≥ 2	≥ 2

4 lepton Signal Region definitions in ttZ analysis

Region	Z_2 leptons	p_T4	p_T34	$\lvert m_{Z_2} - m_Z \rvert$	E_T^miss	$n_{b\text{-tags}}$
4ℓ-DF-1b	$e^\pm\mu^\mp$	–	$> 35\,\text{GeV}$	–	–	1
4ℓ-DF-2b	$e^\pm\mu^\mp$	$> 10\,\text{GeV}$	–	–	–	≥ 2
4ℓ-SF-1b	$e^\pm e^\mp, \mu^\pm\mu^\mp$	–	$> 25\,\text{GeV}$	$> 10\,\text{GeV}$	$> 40\,\text{GeV}$	1
				$< 10\,\text{GeV}$	$> 80\,\text{GeV}$	
4ℓ-SF-2b	$e^\pm e^\mp, \mu^\pm\mu^\mp$	$> 10\,\text{GeV}$	–	$> 10\,\text{GeV}$	-	≥ 2
				$< 10\,\text{GeV}$	$> 40\,\text{GeV}$	

arXiv:1901.03584 (submitted to PRD)

ttZ : ATLAS

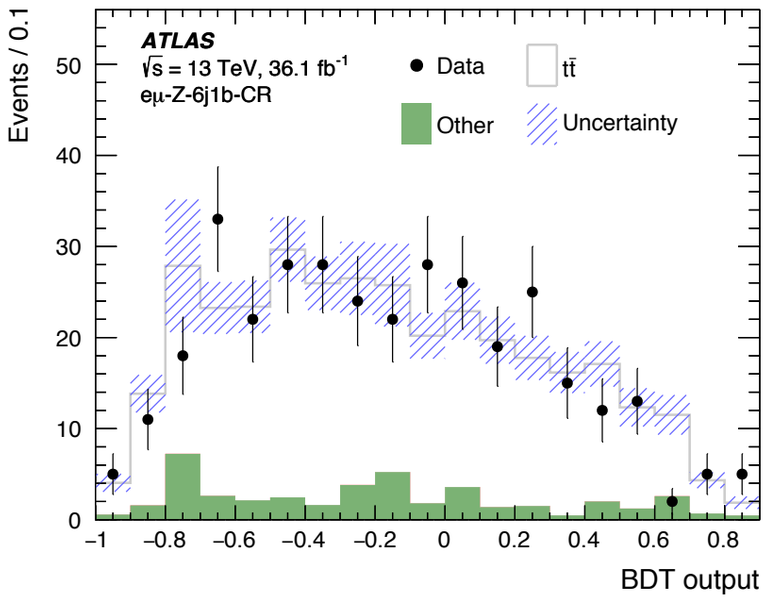
BDT Training Variable in OS 2l final states

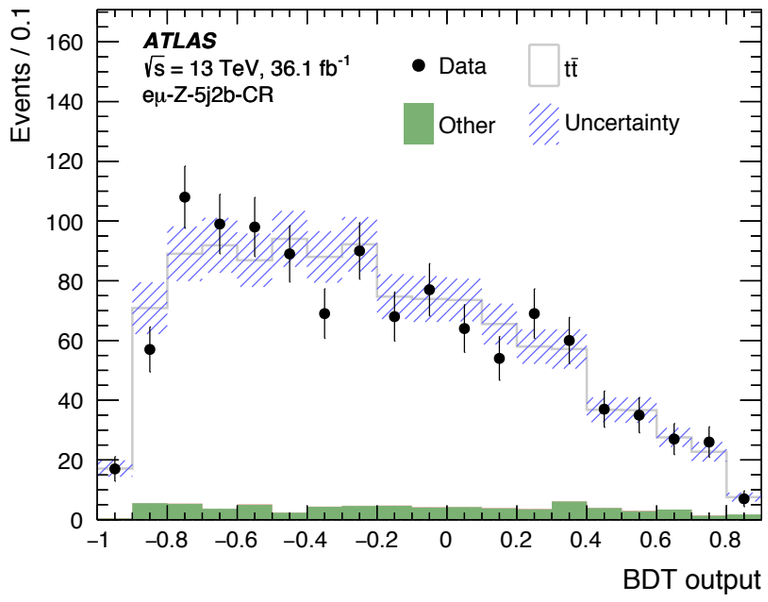
Definition	Ranking 6j1b	5j2b	6j2b
p_{T} of the lepton pair	8	11	8
p_{T} of the fourth jet	6	12	6
p_{T} of the fifth jet	–	14	–
p_{T} of the sixth jet	9	–	11
ΔR_{η} between the two leptons	7	8	12
Number of jet pairs with mass within a window of 30 GeV around 85 GeV	4	6	4
Number of three-jet combinations (containing exactly one b-tagged jet) compatible with a top quark ($\lvert m_{bjj} - m_t \rvert < 15\,GeV$) and ($\lvert m_{jj} - m_W \rvert < 15\,GeV$)	–	–	17
Invariant mass of the two jets with the smallest ΔR_{η}	13	7	14
Invariant mass of the two untagged jets with the highest p_{T}	15	13	–
Invariant mass of the two jets with the highest value of the b-tagging discriminant	–	10	9
Scalar sum of p_{T} divided by the sum of energy of all jets	2	1	2
Average ΔR_{η} of all jet pairs	5	4	5
Maximum invariant mass of a lepton and the b-tagged jet with the smallest ΔR_{η}	14	–	13
First Fox–Wolfram moment built from jets and leptons	3	2	1
Sum of jet p_{T}, using up to six jets	12	5	10
η of dilepton system	1	3	3
Sum of the two closest two-jet invariant masses from jjj_1 and jjj_2 divided by two	10	–	15
ΔR_{η} between two jets with the highest value of the b-tagging discriminant in the event	–	9	7
p_{T} of the b-tagged jet with the highest p_{T}	11	–	16

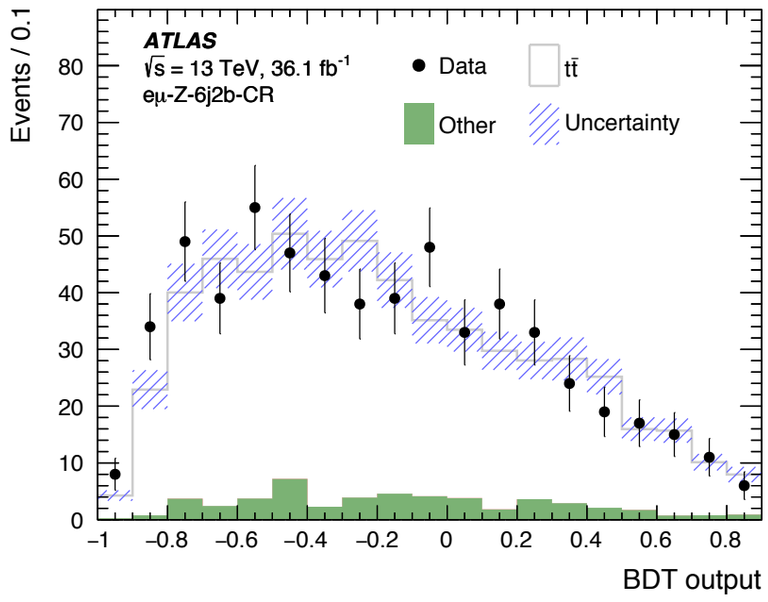
arXiv:1901.03584 (submitted to PRD)

ttZ : ATLAS

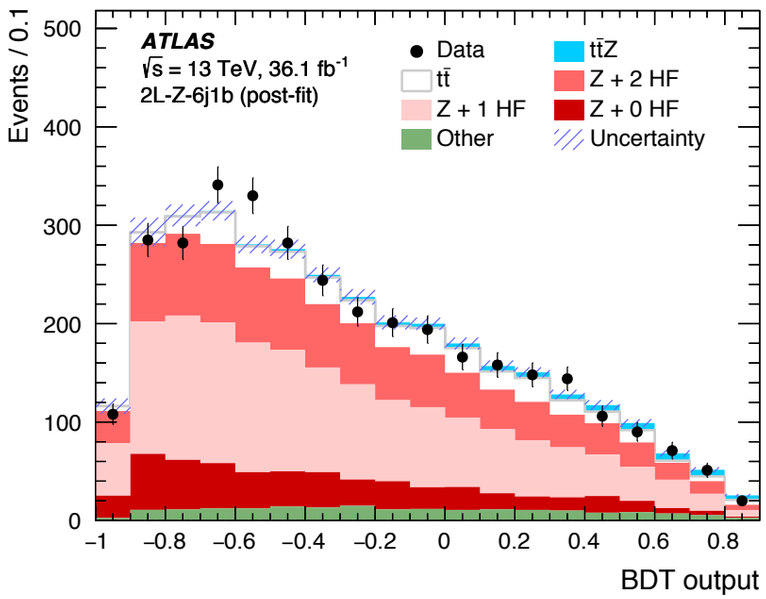
BDT Distributions in OS 2l control regions

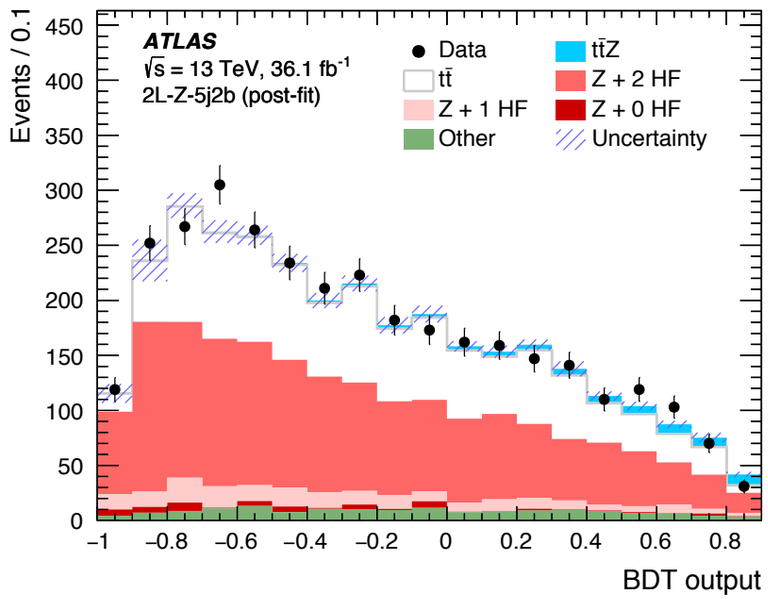


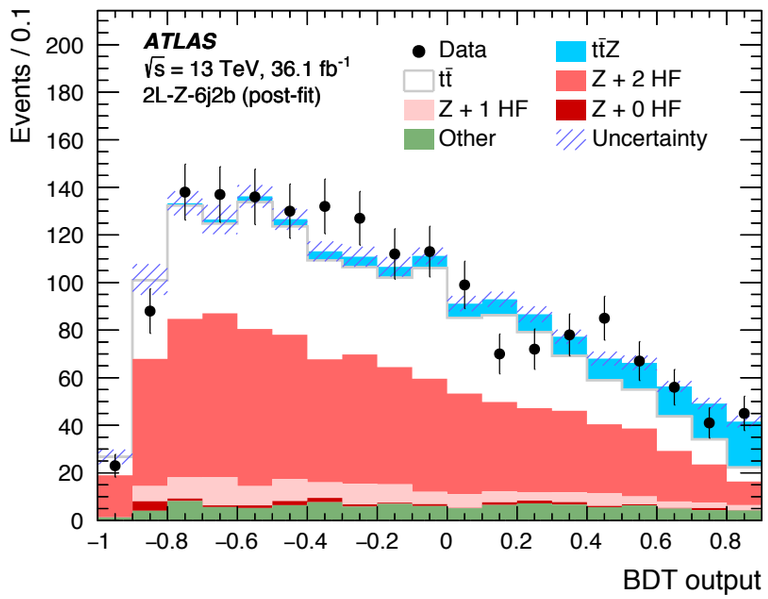




BDT Distributions in OS 2l final states







arXiv:1901.03584 (submitted to PRD)

ttW/ttZ : ATLAS

Systematic Uncertainties

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%

arXiv:1901.03584 (submitted to PRD)

ttW/ttZ : ATLAS

Limits on EFT coefficients

- Five operators which modify the ttZ vertex are studied
- Evaluate effect of new operators on ttZ rate

$$\sigma_{\mathrm{t\bar{t}Z}} = \sigma^{\mathrm{SM}}_{\mathrm{t\bar{t}Z}} + \frac{C_i}{(\Lambda/1\mathrm{TeV})^2}\sigma^{(1)}_i + \frac{C_i^2}{(\Lambda/1\mathrm{TeV})^4}\sigma^{(2)}_{ii}$$

Operator	Expression
$\mathcal{O}^{(3)}_{\phi Q}$	$(\phi^\dagger i \overleftrightarrow{D}^I_\mu \phi)(\bar{Q}\gamma^\mu \tau^I Q)$
$\mathcal{O}^{(1)}_{\phi Q}$	$(\phi^\dagger i \overleftrightarrow{D}_\mu \phi)(\bar{Q}\gamma^\mu Q)$
$\mathcal{O}_{\phi t}$	$(\phi^\dagger i \overleftrightarrow{D}_\mu \phi)(\bar{t}\gamma^\mu t)$
$\mathcal{O}_{tW}$	$(\bar{Q}\sigma^{\mu\nu}\tau^I t)\tilde{\phi}W^I_{\mu\nu}$
$\mathcal{O}_{tB}$	$(\bar{Q}\sigma^{\mu\nu} t)\tilde{\phi}B_{\mu\nu}$

Coefficients	$\mathcal{C}^{(3)}_{\phi Q}/\Lambda^2$	$\mathcal{C}_{\phi t}/\Lambda^2$	$\mathcal{C}_{tB}/\Lambda^2$	$\mathcal{C}_{tW}/\Lambda^2$
Previous indirect constraints at 68% CL	[–4.7, 0.7]	[–0.1, 3.7]	[–0.5, 10]	[–1.6, 0.8]
Previous direct constraints at 95% CL	[–1.3, 1.3]	[–9.7, 8.3]	[–6.9, 4.6]	[–0.2, 0.7]
Expected limit at 68% CL	[–2.1, 1.9]	[–3.8, 2.7]	[–2.9, 3.0]	[–1.8, 1.9]
Expected limit at 95% CL	[–4.5, 3.6]	[–23, 4.9]	[–4.2, 4.3]	[–2.6, 2.6]
Observed limit at 68% CL	[–1.0, 2.7]	[–2.0, 3.5]	[–3.7, 3.5]	[–2.2, 2.1]
Observed limit at 95% CL	[–3.3, 4.2]	[–25, 5.5]	[–5.0, 5.0]	[–2.9, 2.9]
Expected limit at 68% CL (linear)	[–1.9, 2.0]	[–3.0, 3.2]	–	–
Expected limit at 95% CL (linear)	[–3.7, 4.0]	[–5.8, 6.3]	–	–
Observed limit at 68% CL (linear)	[–1.0, 2.9]	[–1.8, 4.4]	–	–
Observed limit at 95% CL (linear)	[–2.9, 4.9]	[–4.8, 7.5]	–	–

arXiv:1901.03584 (submitted to PRD)

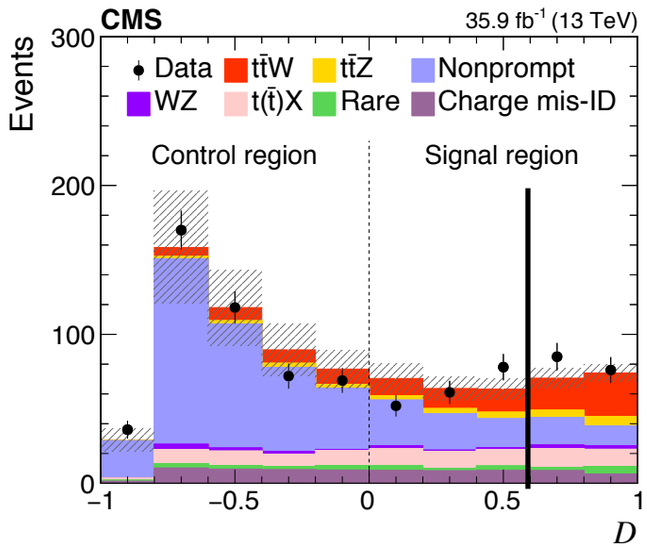
2016 Dataset
35.9 fb^{-1}

ttW/ttZ CMS

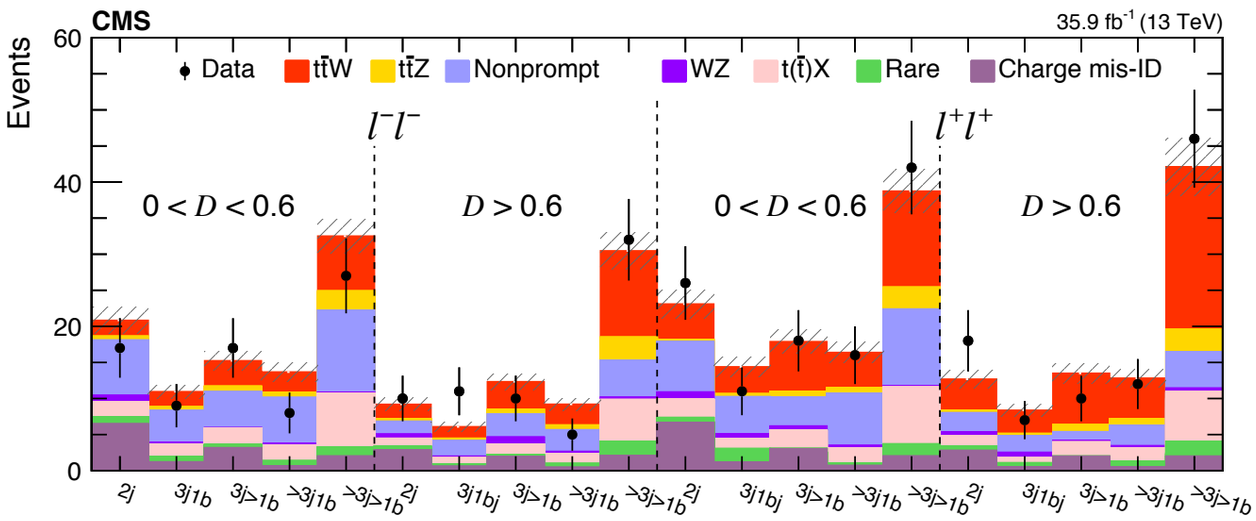
ttW

Selecting same sign dilepton events

BDT discriminant to separate non prompt backgrounds



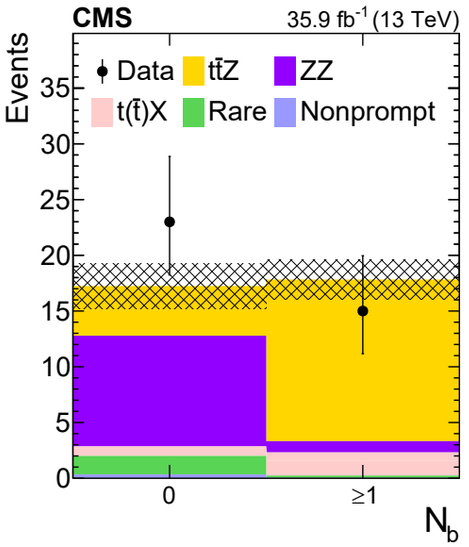
Signal regions defined by jet/bjet multiplicity and BDT output

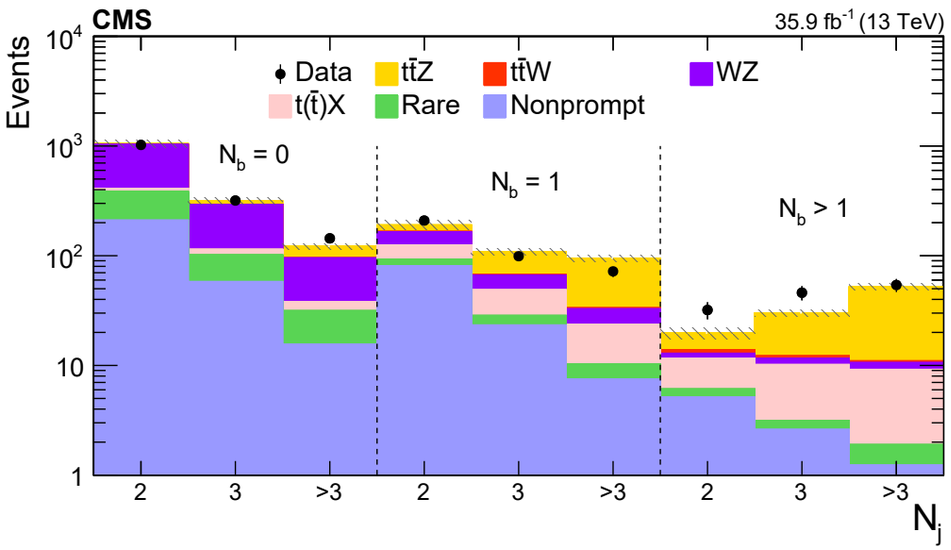


ttZ

Selecting 3 and 4 lepton events

Event yields split by jet/bjet multiplicity





JHEP 08 (2018) 011 (arXiv:1711.02547)

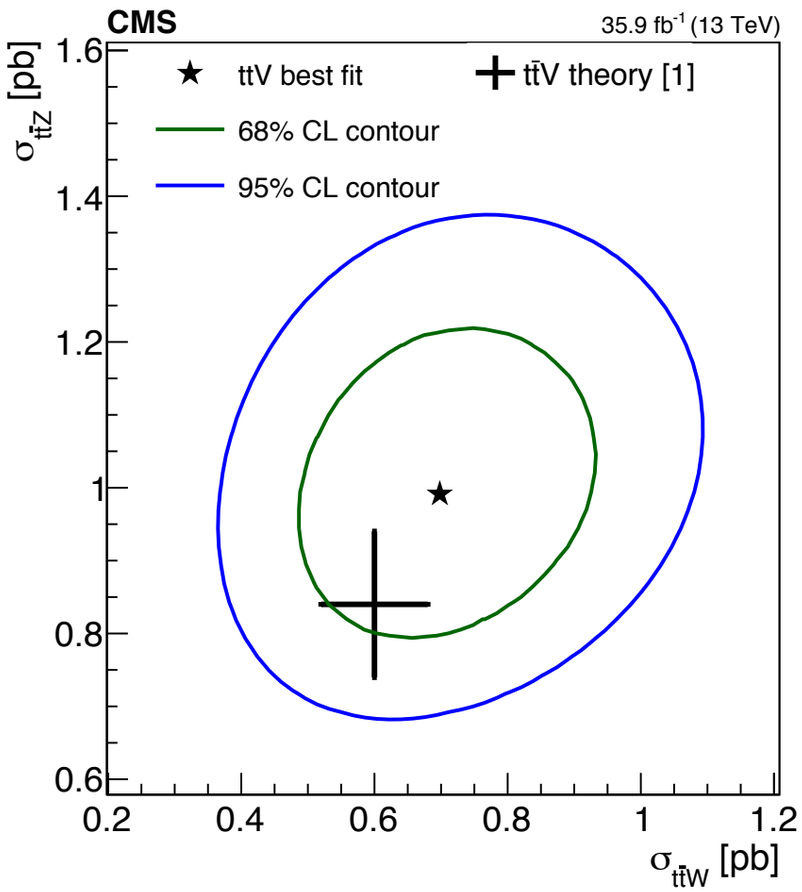
2016 Dataset
35.9 fb^{-1}

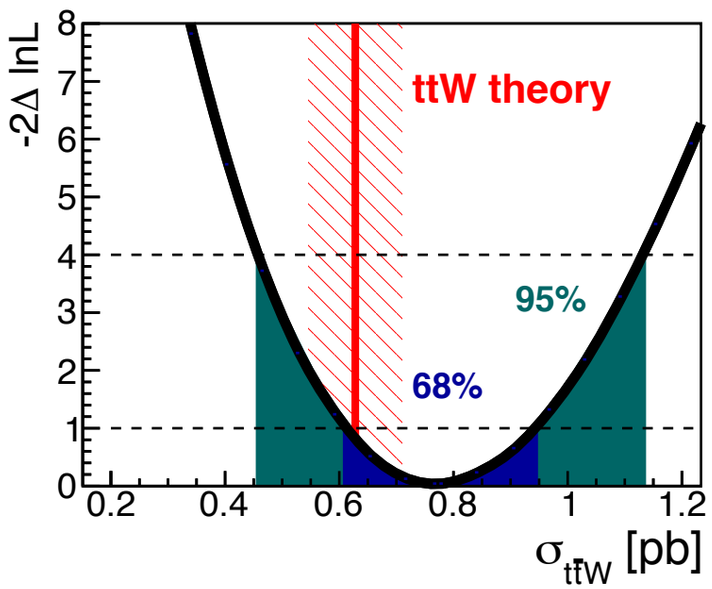
ttW/ttZ CMS

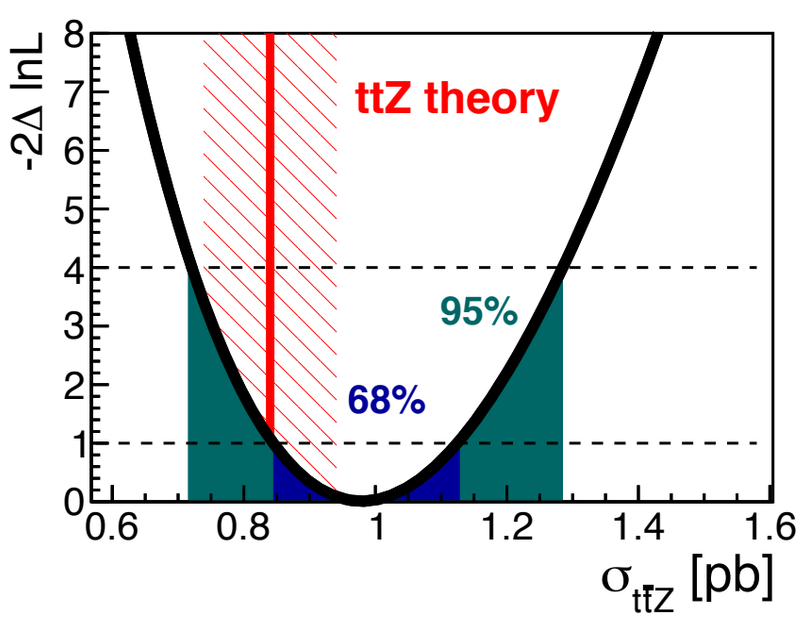
- Simultaneous fits to the ttW and ttZ signal and control regions

$$\sigma(\mathrm{pp} \to \mathrm{t\bar{t}W}) = 0.77^{+0.12}_{-0.11}(\mathrm{stat})^{+0.13}_{-0.12}(\mathrm{syst})\ \mathrm{pb}$$
$$\sigma(\mathrm{pp} \to \mathrm{t\bar{t}W^{+}}) = 0.58 \pm 0.09(\mathrm{stat})^{+0.09}_{-0.08}(\mathrm{syst})\ \mathrm{pb}$$
$$\sigma(\mathrm{pp} \to \mathrm{t\bar{t}W^{-}}) = 0.19 \pm 0.07(\mathrm{stat}) \pm 0.06(\mathrm{syst})\ \mathrm{pb}$$
$$\sigma(\mathrm{pp} \to \mathrm{t\bar{t}Z}) = 0.99^{+0.09}_{-0.08}(\mathrm{stat})^{+0.12}_{-0.10}(\mathrm{syst})\ \mathrm{pb}$$

- Uncertainties dominated by:
  - ttZ: Lepton ID, trigger, and b-tagging efficiencies
  - ttW: Trigger and b-tagging efficiencies, non prompt background uncertainty







JHEP 08 (2018) 011 (arXiv:1711.02547)

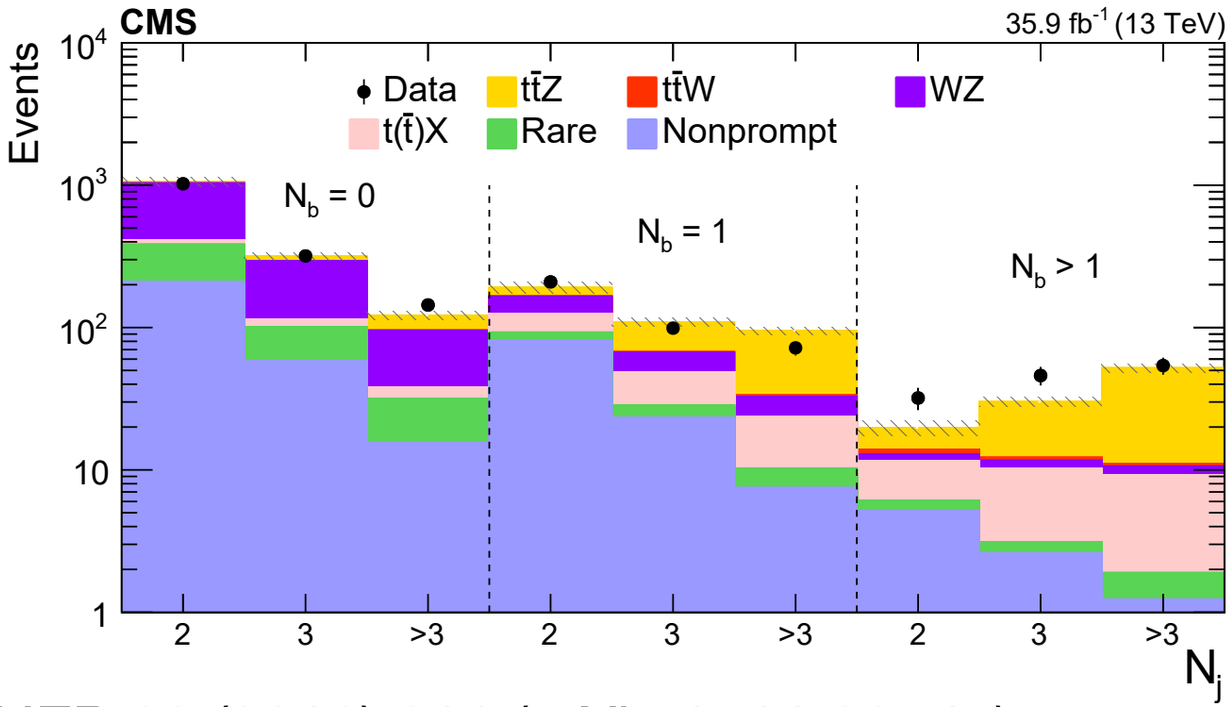
2016 Dataset
35.9 fb^{-1}

ttZ: CMS (2016)

- Event selection for both three-lepton and four-lepton final states

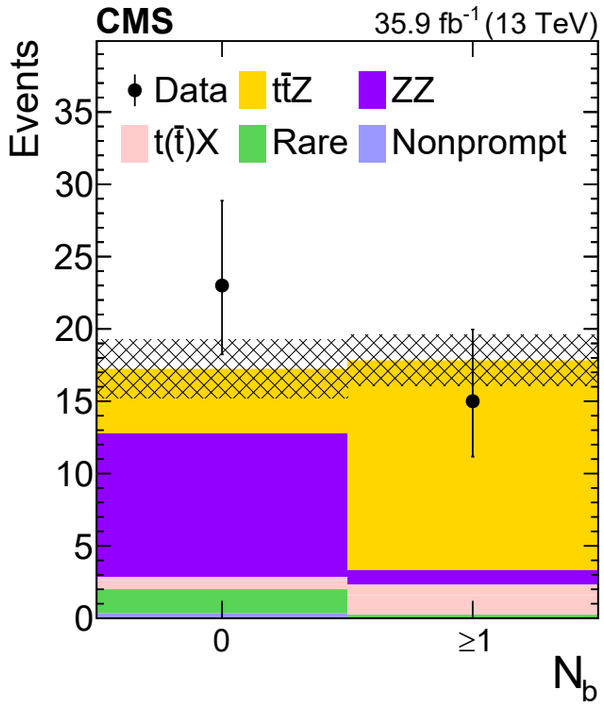
Three-leptons

- Exactly three leptons (μμμ,μμe,μee,eee)
- One opposite sign/ same flavor (OS SF) pair with $|m_{\ell\ell}-m_Z| < 10$ GeV
- Form 9 exclusive bins
  - N_j=2,3,>3
  - N_b=0,1,>1



Four-leptons

- Exactly four leptons, 2 ℓ^+, 2 ℓ^-
- One OS SF pair with $|m_{\ell\ell}-m_Z| < 20$ GeV
  - Veto μμμμ, μμee, or eeee events with second pair in mass peak
- Require ≥2 jets, split in 0b & ≥1b

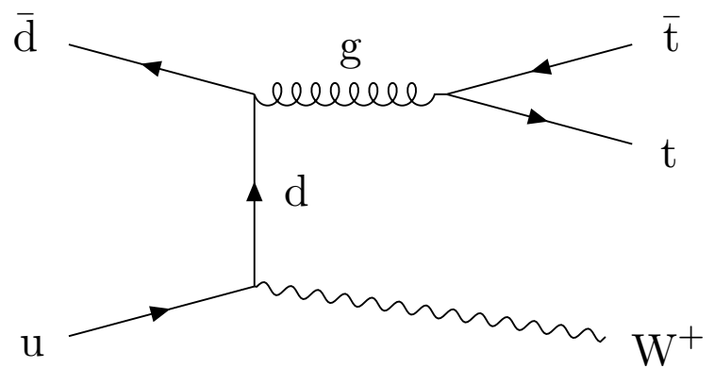


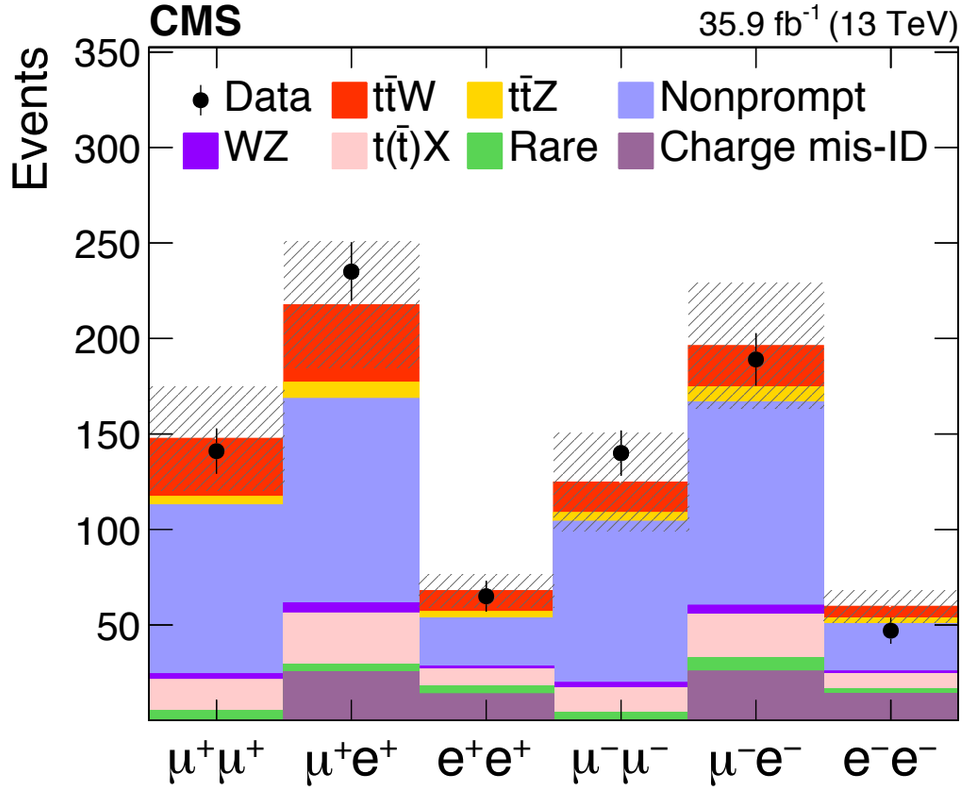
JHEP 08 (2018) 011 (arXiv:1711.02547)

2016 Dataset
35.9 fb^{-1}

ttW: CMS

- Analysis selects same-sign dilepton events
  - Exactly 2 leptons (e or μ) with same sign
  - At least 2 jets and 1 b-tag
  - Reject events with $m_{\ell\ell} < 12$ GeV or dielectron events with $|m_{\ell\ell}-m_Z| < 15$ GeV
  - $p_T^{miss} > 30$ GeV
- Backgrounds:
  - Nonprompt leptons: estimated from loose selection sideband (tight-to-loose ratio)
  - Misidentified charge
  - t(t)+X (ttH, tZq, tWZ, tWq, …)
  - Rare (WW, ZZ, Wγ, Zγ, triboson)



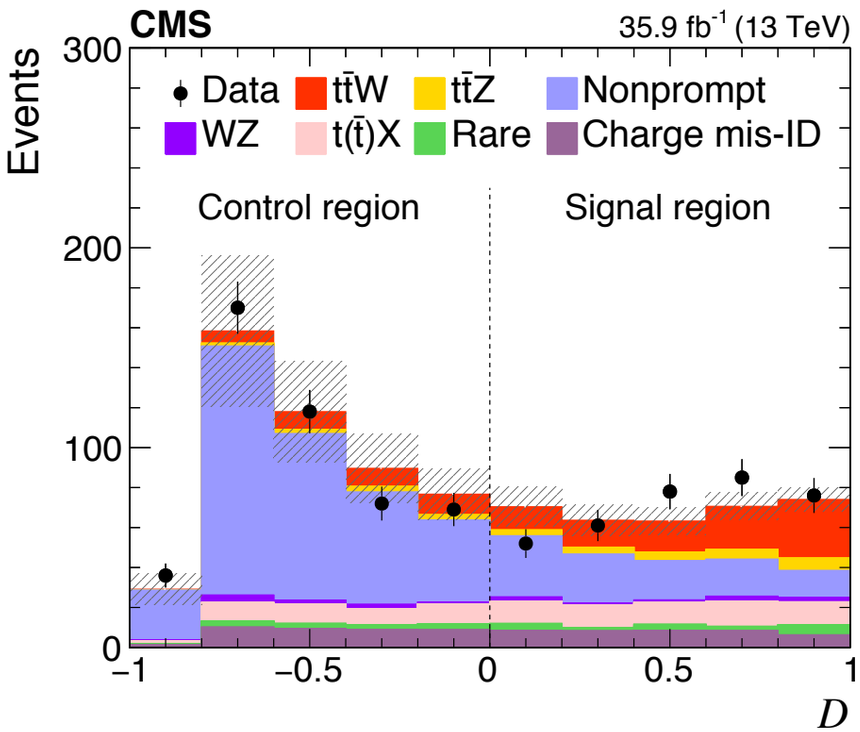


JHEP 08 (2018) 011 (arXiv:1711.02547)

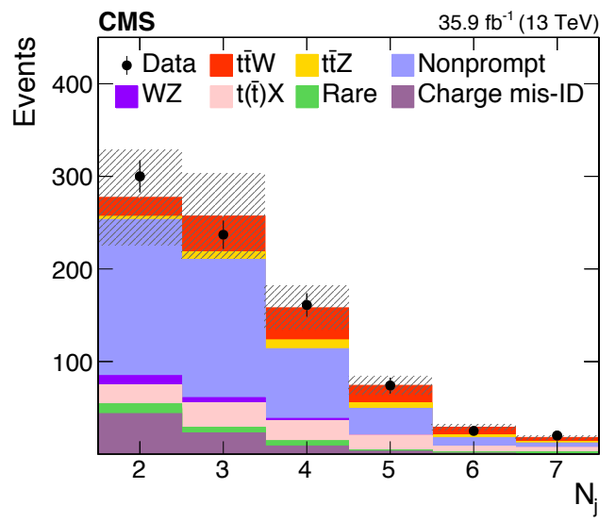
2016 Dataset
35.9 fb^{-1}

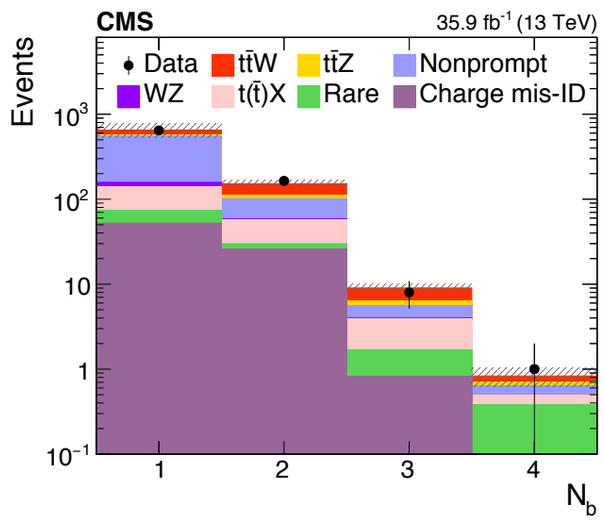
ttW: CMS

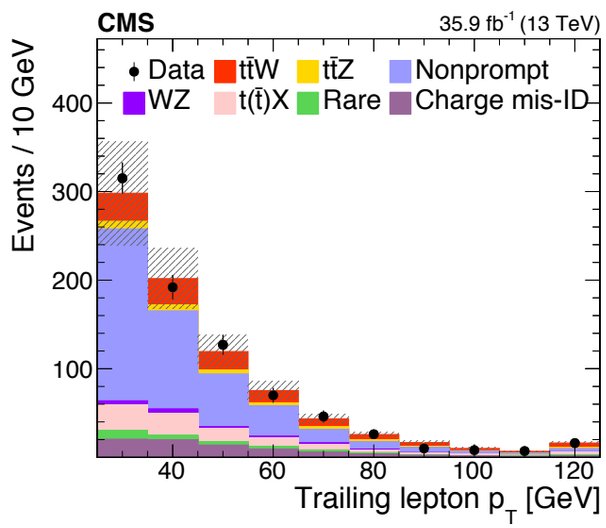
- Boosted Decision Tree classifier used to discriminate signal from non-prompt background
  - Using jet/b-jet multiplicities, and lepton/jet kinematics
- BDT discriminant (D) used to separate signal region (D>0) and control region (D<0)

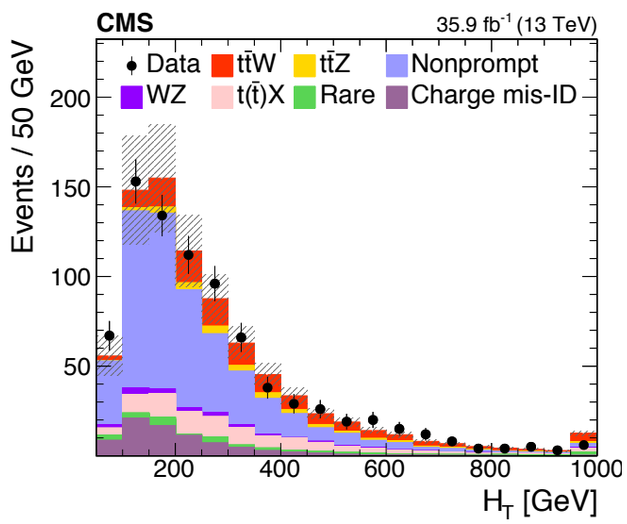


- N_{j}
- N_{b}
- p_{T} leading lepton
- p_{T} trailing lepton
- M_{T} leading lepton
- H_{T}: scalar sum of p_{T} of jets
- $p_{\mathrm{T}}^{\mathrm{miss}}$
- p_{T} leading and second leading jets
- ΔR between trailing lepton and nearest jet







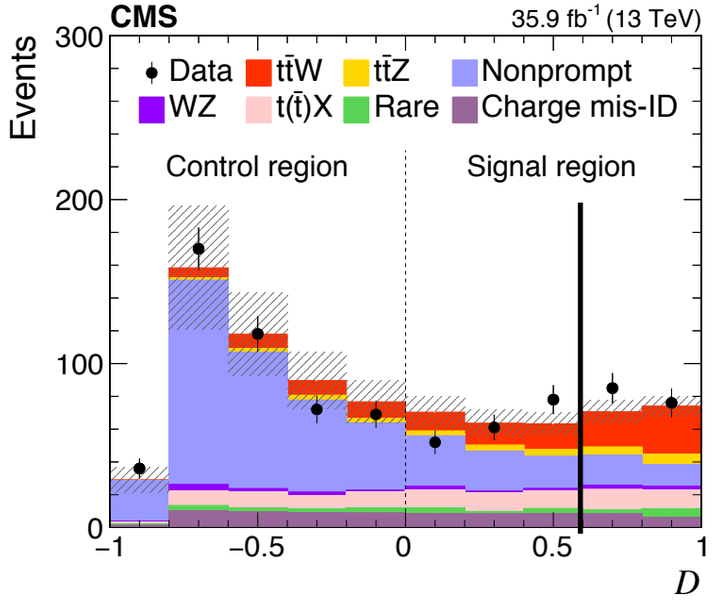


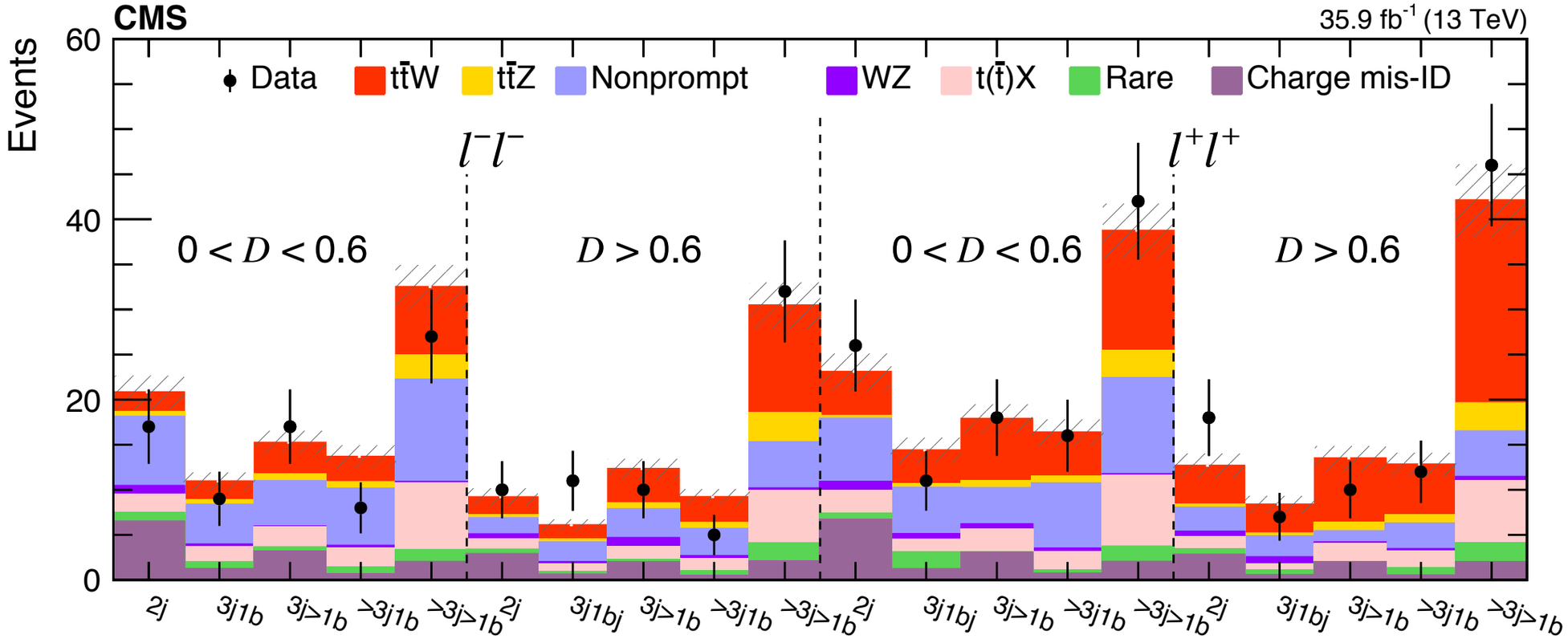
JHEP 08 (2018) 011 (arXiv:1711.02547)

2016 Dataset
35.9 fb^{-1}

ttW: CMS

- Signal region split up to define 20 exclusive signal regions
  - Split $\ell^+\ell^+$ from $\ell^-\ell^-$ to take advantage of difference between ttW$^+$ and ttW$^-$
  - Split in 0<D<0.6 and D>0.6
  - Define exclusive jet/b-jet multiplicity bins
    - =2j, =3j=1b, =3j>1b, >3j=1b, >3j>1b





JHEP 08 (2018) 011 (arXiv:1711.02547)

2016 Dataset
35.9 fb^{-1}

ttW/ttZ CMS (2016)

Systematic uncertainties

Source	Uncertainty from each source (%)	Impact on the measured $t\bar{t}W$ cross section (%)	Impact on the measured $t\bar{t}Z$ cross section (%)
Integrated luminosity	2.5	4	3
Jet energy scale and resolution	2–5	3	3
Trigger	2–4	4–5	5
B tagging	1–5	2–5	4–5
PU modeling	1	1	1
Lepton ID efficiency	2–7	3	6–7
Choice in μ_R and μ_F	1	<1	1
PDF	1	<1	1
Nonprompt background	30	4	<2
WZ cross section	10–20	<1	2
ZZ cross section	20	—	1
Charge misidentification	20	3	—
Rare SM background	50	2	2
$t(\bar{t})X$ background	10–15	4	3
Stat. unc. in nonprompt background	5–50	4	2
Stat. unc. in rare SM backgrounds	20–100	1	<1
Total systematic uncertainty	—	14	12

JHEP 08 (2018) 011 (arXiv:1711.02547)

2016/17 Dataset
77.5 fb^{-1}

ttZ CMS (2016/17)

Systematic uncertainties

Source	Uncertainty range (%)	Correlated in 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	10–20	✓	3
WZ + heavy flavor	8	✓	1
ZZ cross section	10	✓	1
$t(\bar{t})X$ bg.	10–15	✓	3
$X\gamma$ background	20	✓	1
Nonprompt background	30	✓	< 1
Rare SM background	50	✓	2
Stat. unc. in nonprompt bg.	5–50	×	< 1
Stat. unc. in rare SM bg.	5–100	×	< 1
Total uncertainty			7

CMS PAS TOP-18-009

2016/17 Dataset
77.5 fb^{-1}

ttZ EFT Limits CMS

Signal and control region definitions used in EFT limit analysis

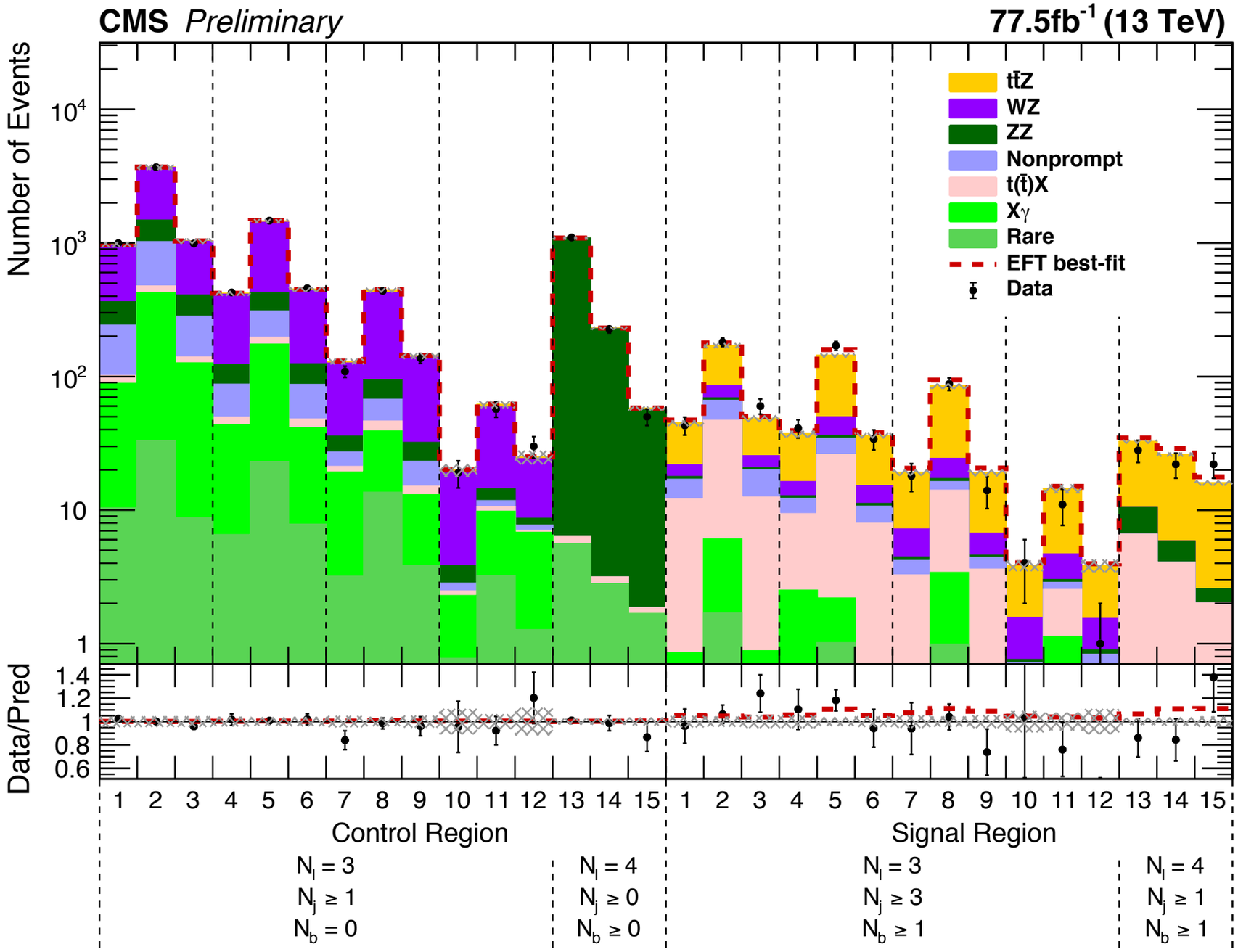
N_ℓ	N_j	N_b	N_Z	$p_T(Z)$ (GeV)	$-1 \leq \cos(\theta^*) < -0.6$	$-0.6 \leq \cos(\theta^*) < 0.6$	$0.6 \leq \cos(\theta^*)$
3	≥ 3	≥ 1	1	0–100	SR1	SR2	SR3
				100–200	SR4	SR5	SR6
				200–400	SR7	SR8	SR9
				≥ 400	SR10	SR11	SR12
4	≥ 1	≥ 1	1	0–100	SR13		
				100–200	SR14		
				≥ 200	SR15		
3	≥ 1	0	1	0–100	CR1	CR2	CR3
				100–200	CR4	CR5	CR6
				200–400	CR7	CR8	CR9
				≥ 400	CR10	CR11	CR12
4	≥ 1	≥ 0	2	0–100	CR13		
				100–200	CR14		
				≥ 200	CR15		

CMS PAS TOP-18-009

2016/17 Dataset
77.5 fb^{-1}

ttZ EFT Limits CMS

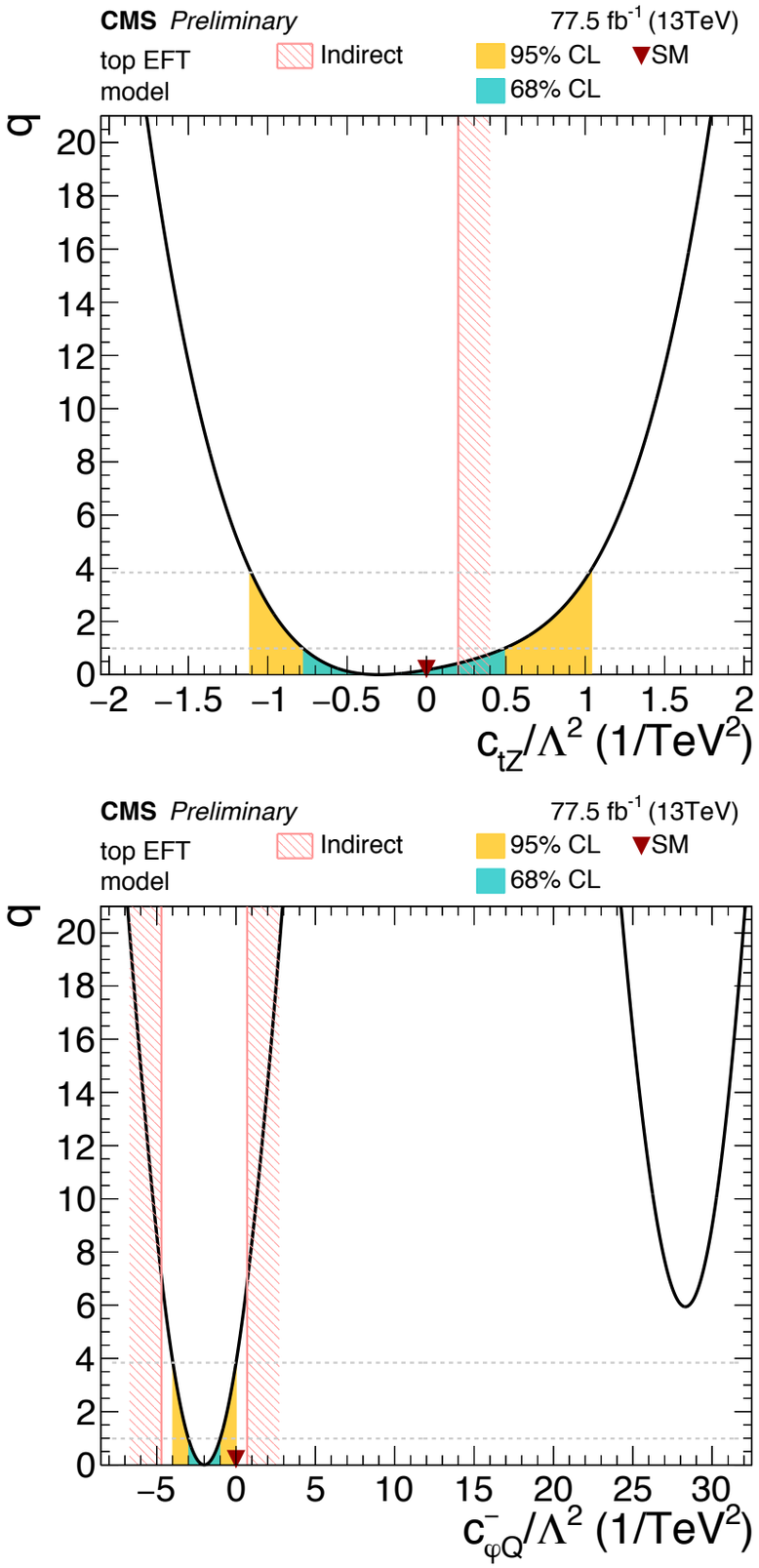
Signal and control region yields used in EFT limit analysis

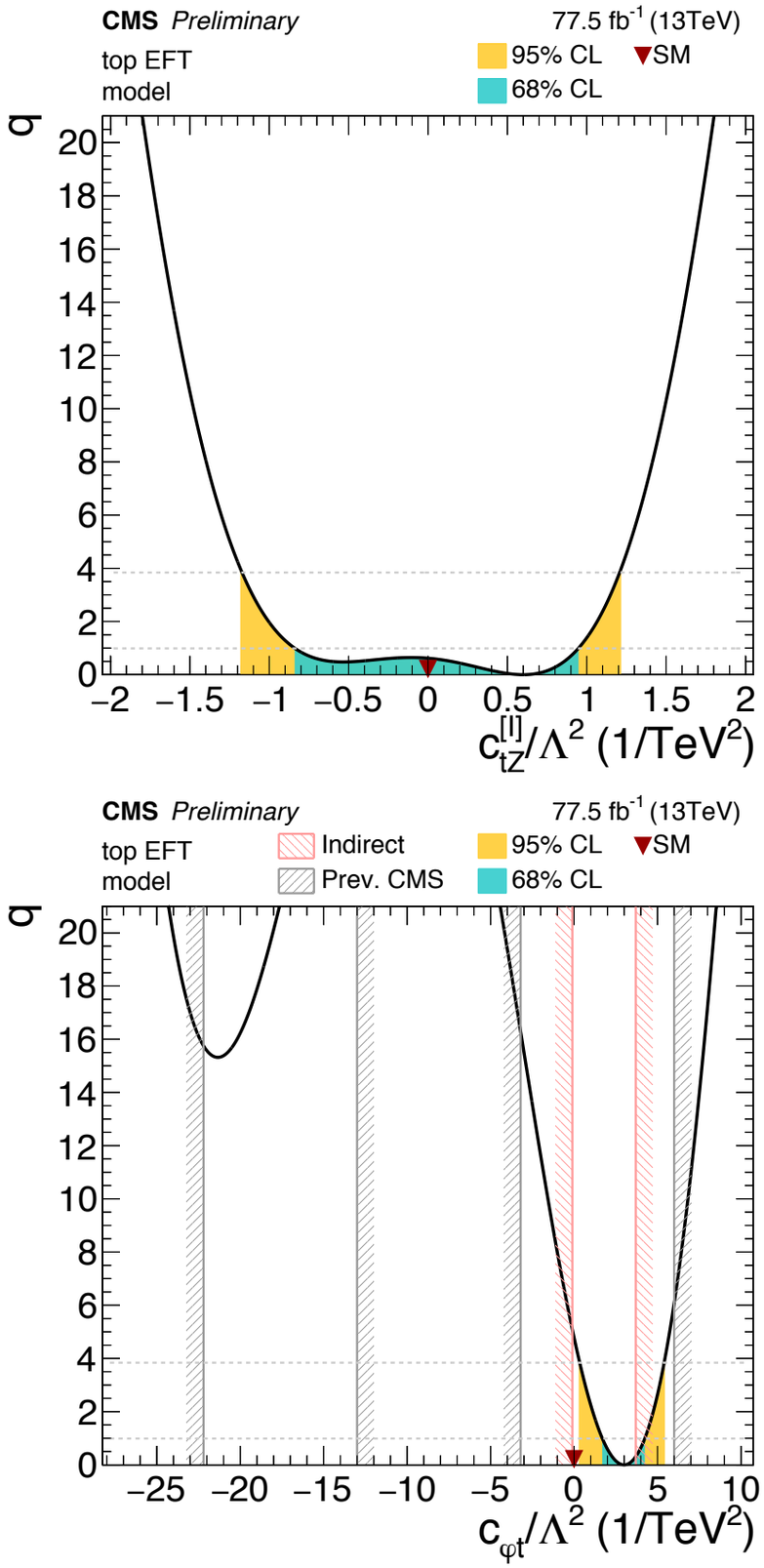


CMS PAS TOP-18-009

ttZ EFT Limits CMS

One dimensional fit results for limits on EFT coefficients Other coefficients set to 0 when not being profiled

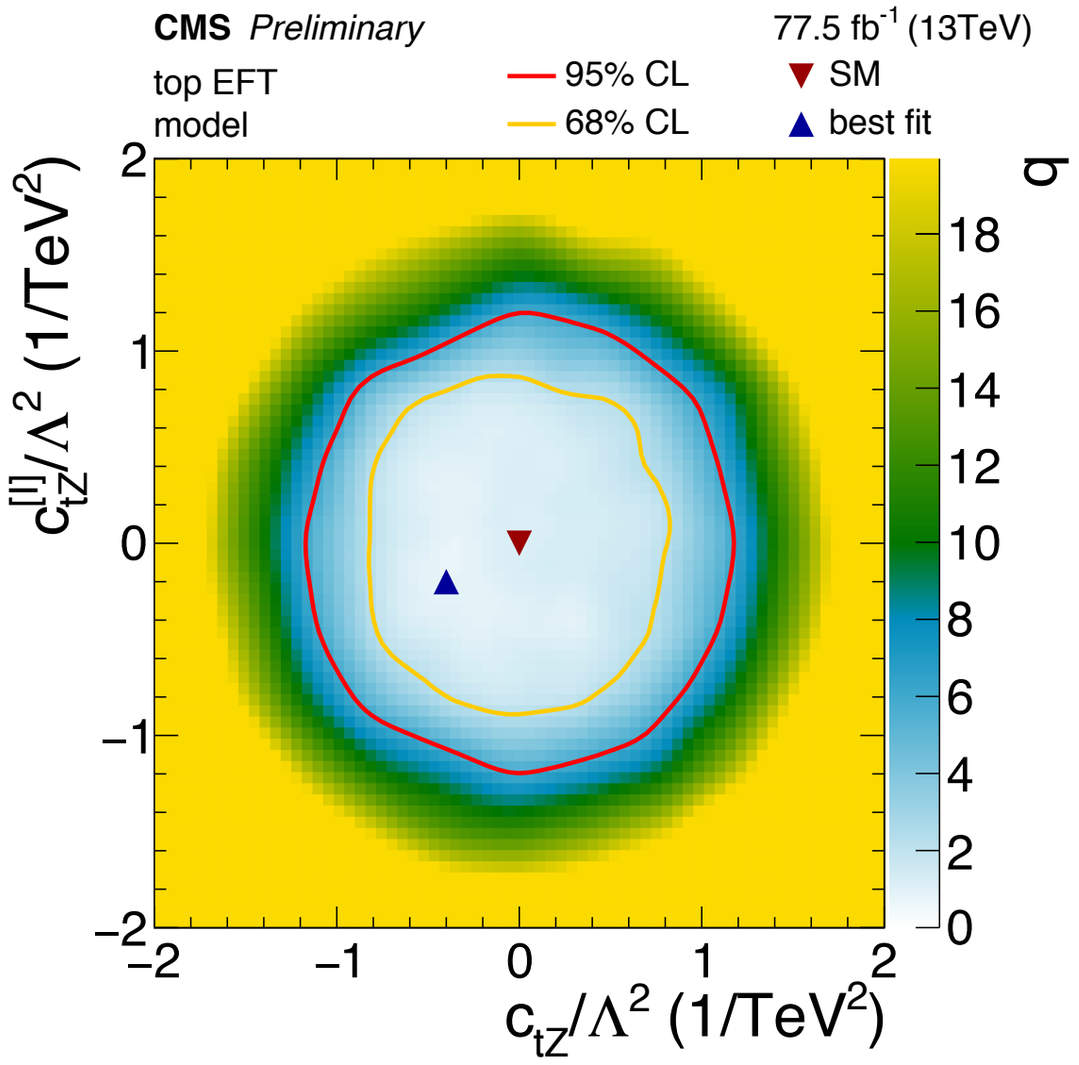


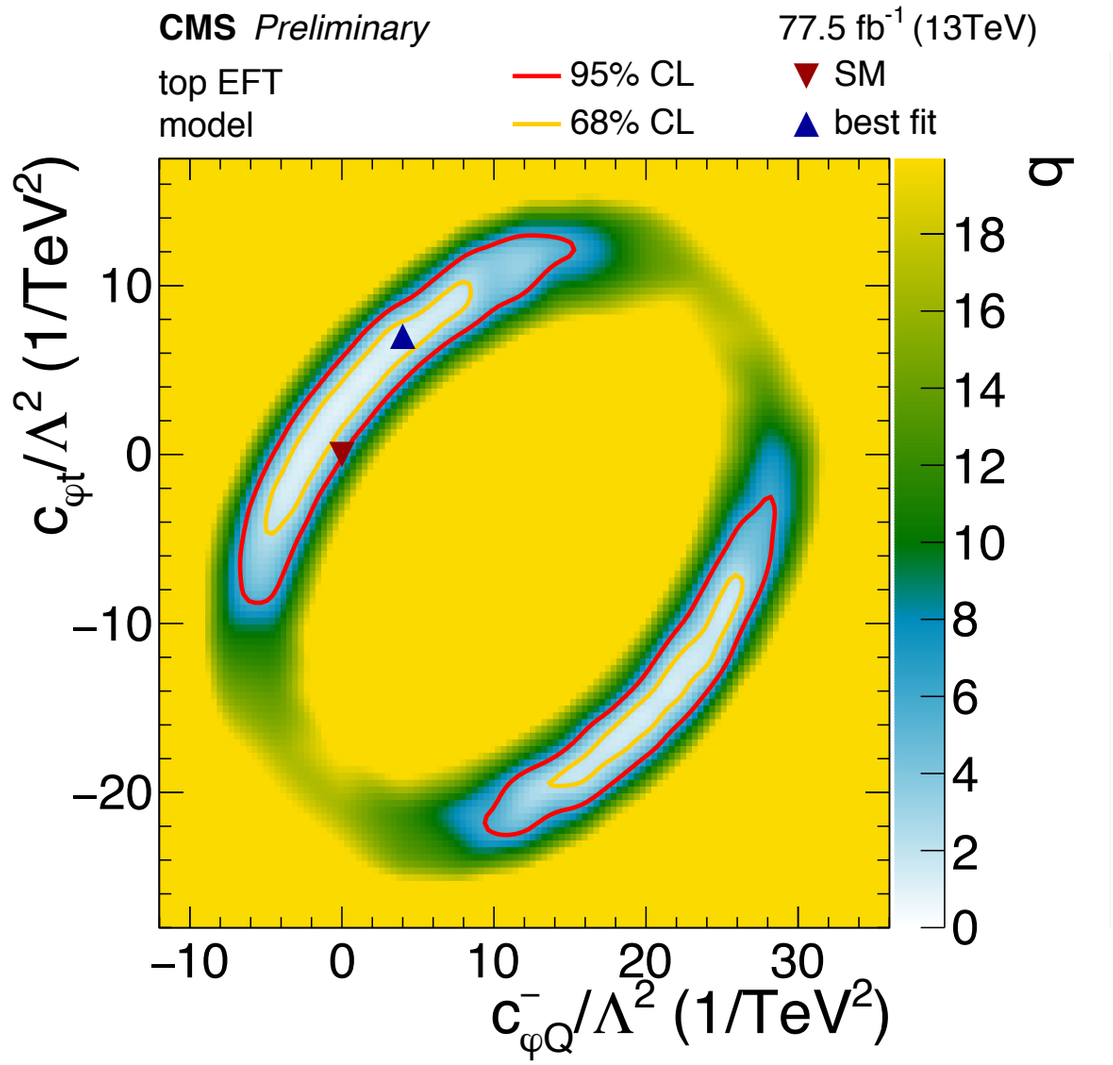


CMS PAS TOP-18-009

ttZ EFT Limits CMS

Two dimensional fit results for limits on EFT coefficients
Other coefficients set to 0 when not being profiled



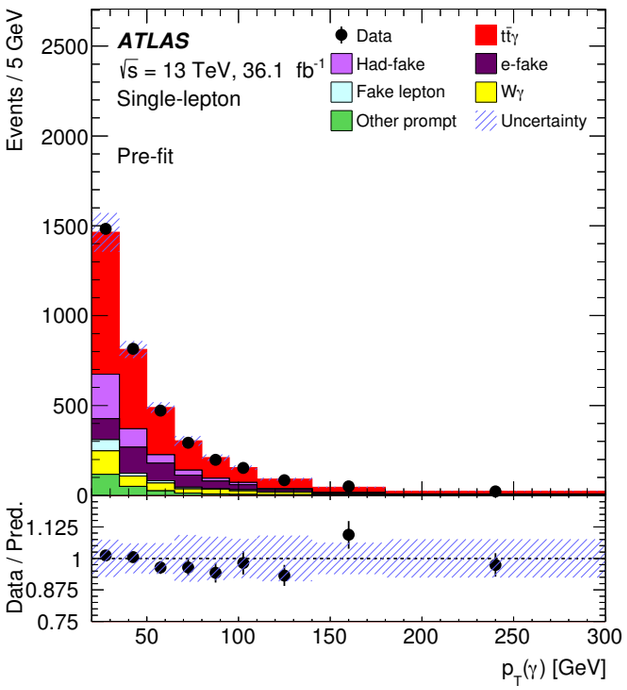


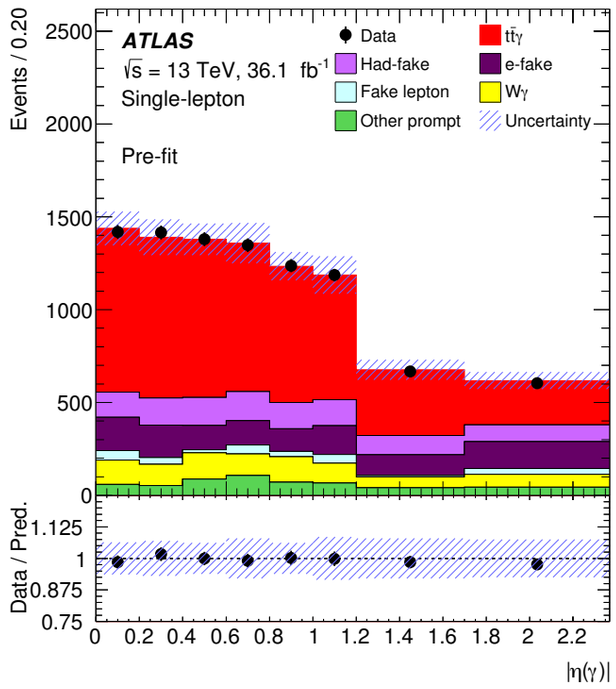
CMS PAS TOP-18-009

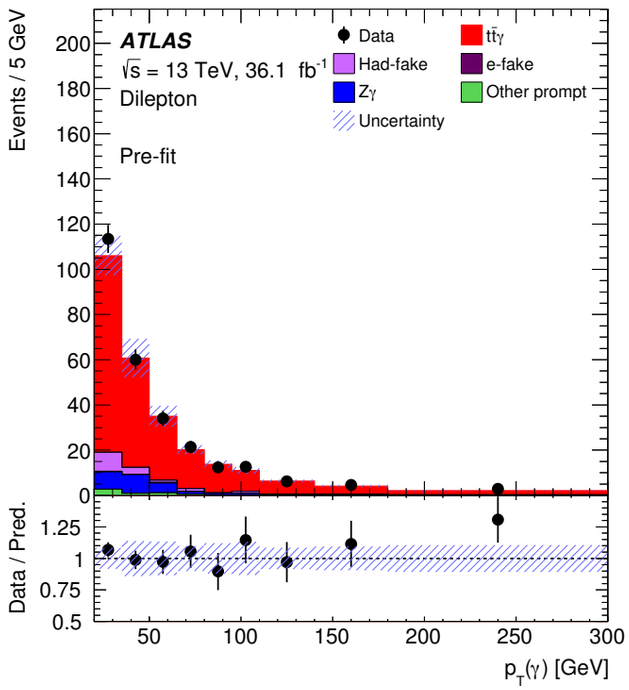
ttγ ATLAS

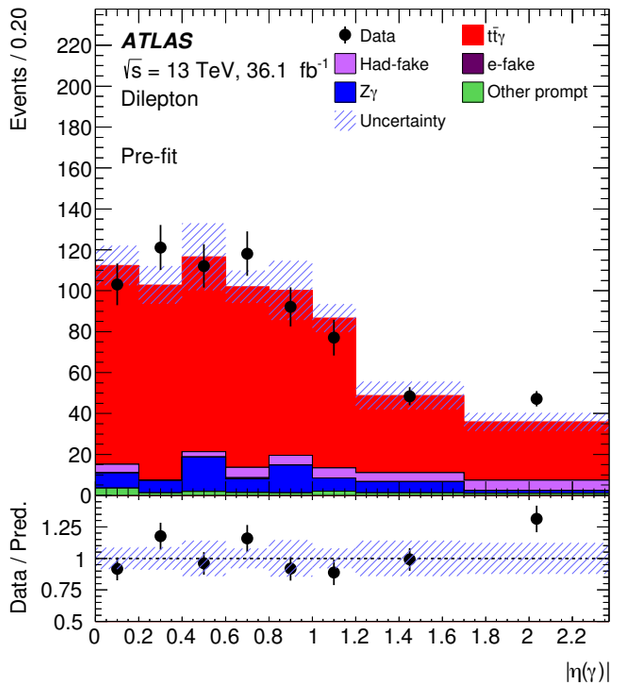
Event selection requirements

e+jets	μ+jets	ee	$\mu\mu$	$e\mu$
Primary vertex				
1 e	1 μ	2 e, OS	2 μ, OS	1 e + 1 μ, OS
Trigger match				
$\geq$ 4 jets		$\geq$ 2 jets		
$\geq$ 1 b-jet				
1 γ				
$\lvert m(e,\gamma) - m(Z)\rvert > 5$ GeV		-		
-		$m(\ell,\ell) \notin$ [85,95] GeV		-
-		$m(\ell,\ell,\gamma) \notin$ [85,95] GeV		-
-		$E_{\mathrm{T}}^{\mathrm{miss}} > 30$ GeV		-
-		$m(\ell,\ell) > 15$ GeV		
$\Delta R(\gamma,\ell) > 1.0$				



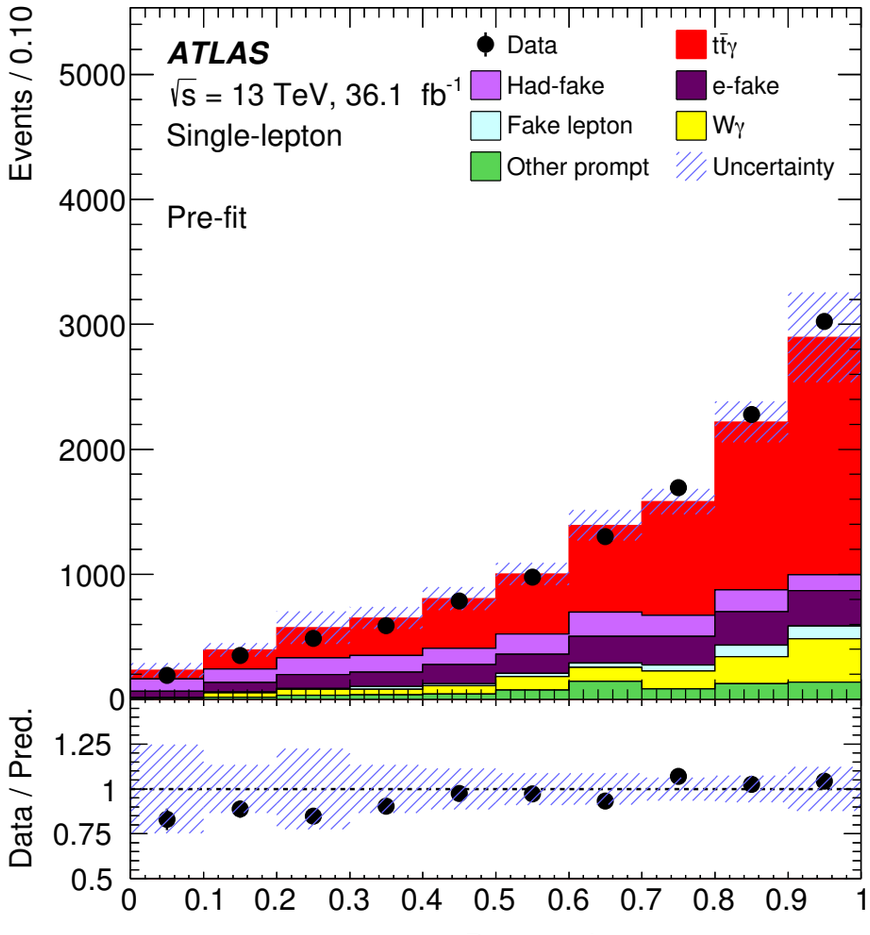


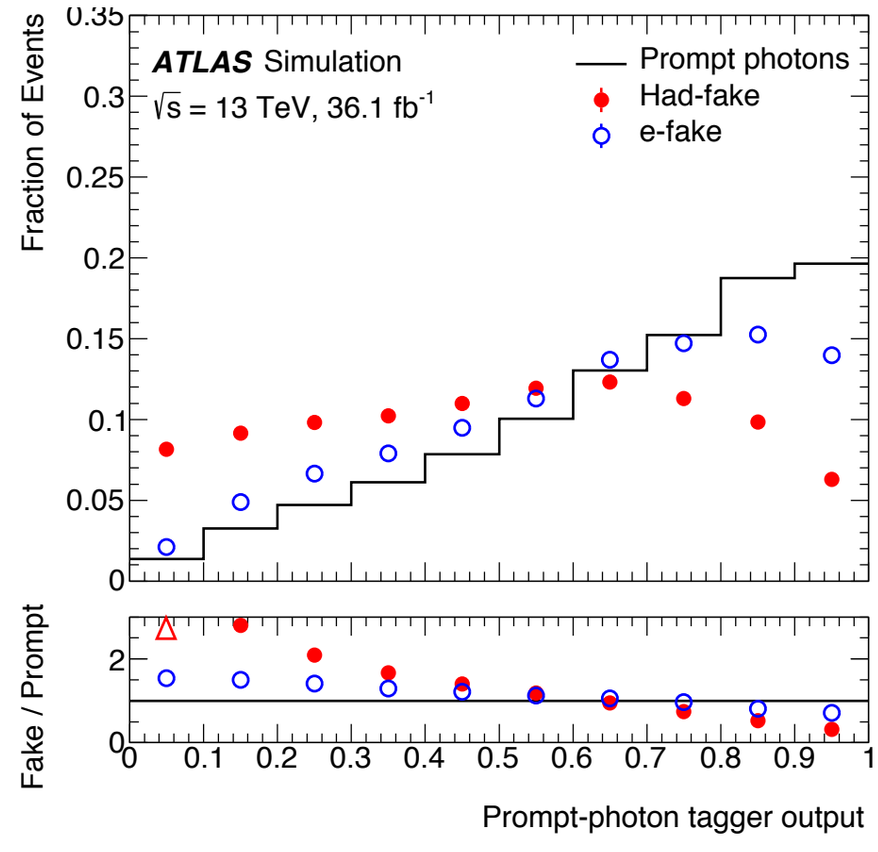




arXiv:1812.01697 (submitted to EPJC)

ttγ ATLAS





Input variables to the Prompt Photon Tagger

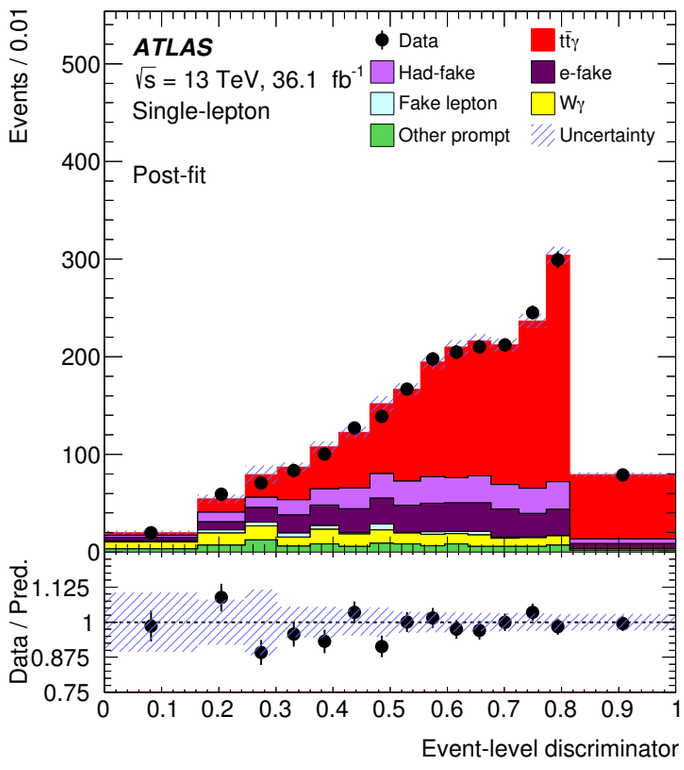
Name	Description
Hadronic leakage	
R_{had} or R_{had_1}	Transverse energy leakage in the hadronic calorimeter normalized to transverse energy of the photon candidate in the ECAL. In the region $0.8 \leq \lvert\eta\rvert \leq 1.37$, the entire energy of the photon candidate in the HCAL is used (R_{had}), while in the region $\lvert\eta\rvert < 0.8$ and $\lvert\eta\rvert > 1.37$ the energy of the first layer of the HCAL is used (R_{had1}).
Energy ratios and width in the second layer of ECAL	
R_η	Energy ratio of 3×7 to 7×7 cells in the $\eta \times \phi$ plane.
R_ϕ	Energy ratio of 3×3 to 3×7 cells in the $\eta \times \phi$ plane.
w_{η_2}	Lateral width of the shower, using a window of $\eta \times \phi = 3 \times 5$ cells.
Energy ratios and widths in the first (strip) layer of ECAL	
w_{s3}	Shower width along η, using 3 strips around the largest energy deposit.
$w_{s\,\text{tot}}$	Shower width along η, using 20×2 strip cells in the $\eta \times \phi$ plane.
F_{side}	Energy outside the 3 central strips but within 7 strips, normalized to the energy within the 3 central strips.
E_{ratio}	Ratio between difference of the first and second energy maximum divided by their sum ($E_{\text{ratio}} = 1$ if there is no second maximum).
ΔE	Difference between the second energy maximum and the minimum found between first and second maximum ($\Delta E = 0$ if there is no second maximum).

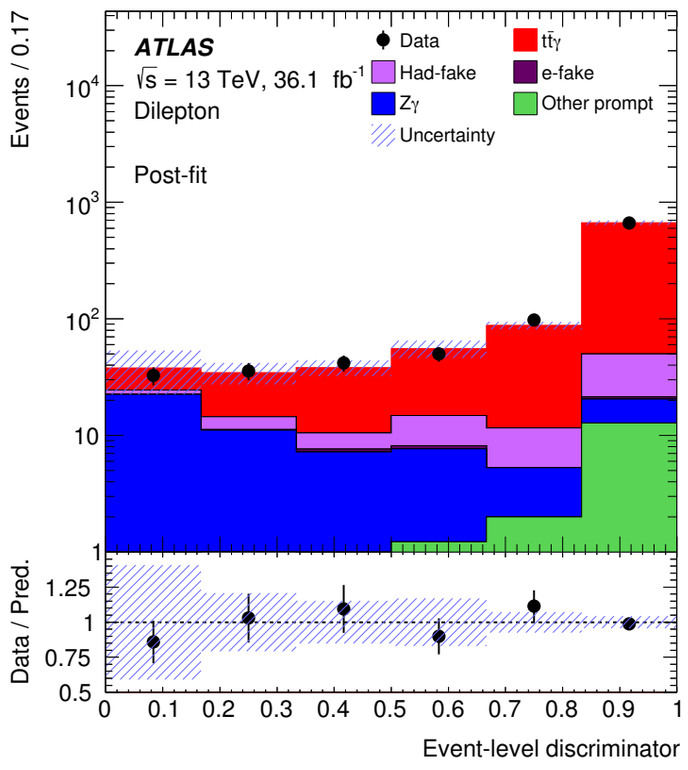
arXiv:1812.01697 (submitted to EPJC)

ttγ ATLAS

Input variables to the Event Level Discrimator

Variable	Description	Single lepton	Dilepton
PPT	Prompt-photon tagger output	✓	
H_{T}	Scalar sum of the p_{T} of the leptons and jets	✓	
$m(\gamma,\ell)$	Invariant mass of the system of the photon and the lepton	✓	
$E_{\mathrm{T}}^{\mathrm{miss}}$	Missing transverse energy	✓	✓
m_W^{T}	Reconstructed transverse mass of the leptonically decaying W-boson $= \sqrt{2 \times p_{\mathrm{T}}(\ell) \times E_{\mathrm{T}}^{\mathrm{miss}} \times (1 - \cos(\Delta\phi(\ell, E_{\mathrm{T}}^{\mathrm{miss}})))}$	✓	
N_{jets}	Jet multiplicity	✓	
$p_{\mathrm{T}}(j_1)$	p_{T} of the leading jet (ordered in p_{T})	✓	✓
$p_{\mathrm{T}}(j_2)$	p_{T} of the sub-leading jet	✓	✓
$p_{\mathrm{T}}(j_3)$	p_{T} of the third jet	✓	
$p_{\mathrm{T}}(j_4)$	p_{T} of the fourth jet	✓	
$p_{\mathrm{T}}(j_5)$	p_{T} of the fifth jet	✓	
$N_{b\text{-jets}}$	b-jet multiplicity	✓	✓
$b_1(j)$	highest b-tagging score of all jets	✓	✓
$b_2(j)$	second highest b-tagging score of all jets	✓	✓
$b_3(j)$	third highest b-tagging score of all jets	✓	
$m(\ell,\ell)$	Invariant mass of the system of the two leptons		✓

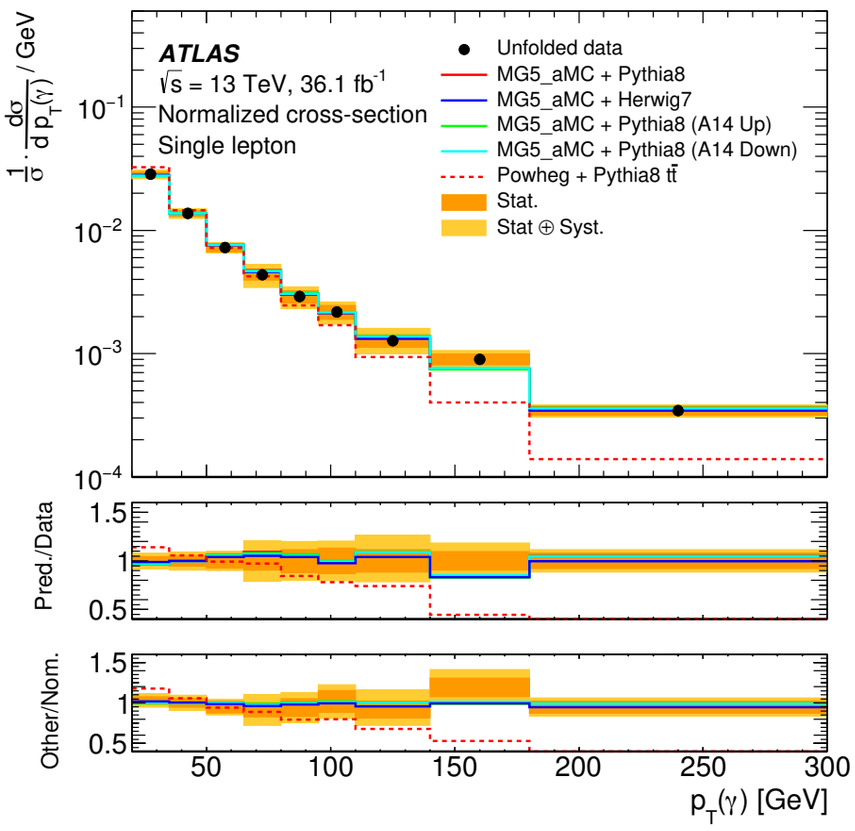


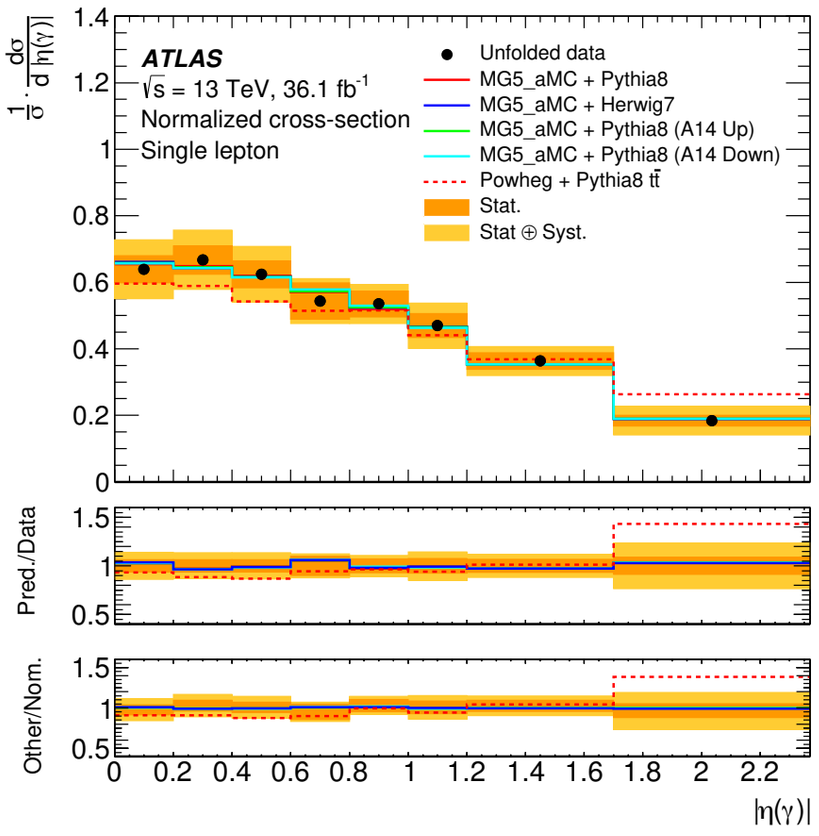


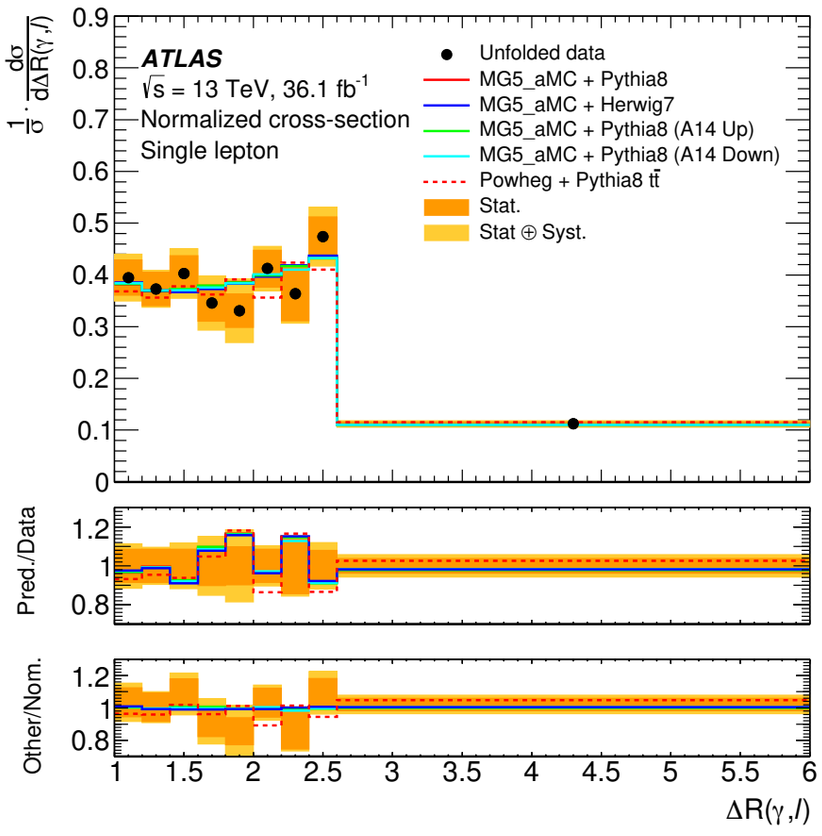
arXiv:1812.01697
(submitted to EPJC)

$t\bar{t}\gamma$ ATLAS

Differential cross section measurements in single lepton final state



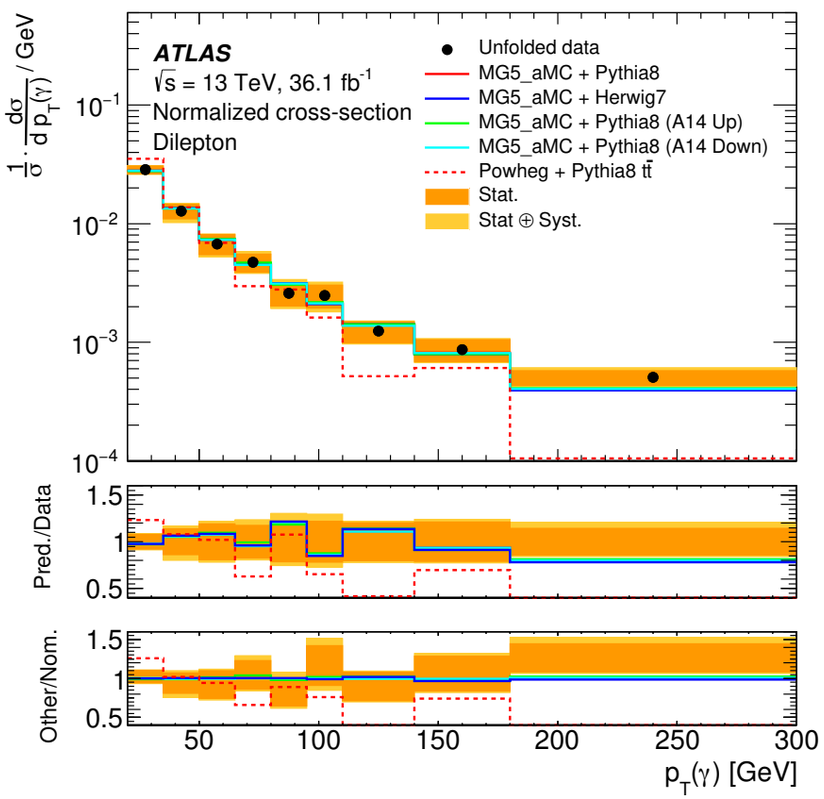


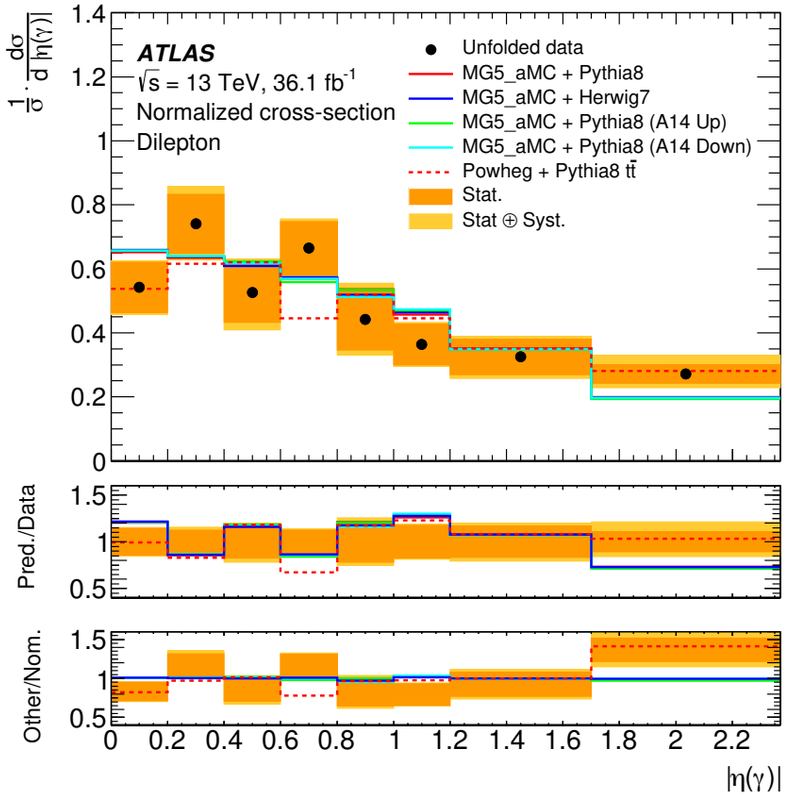


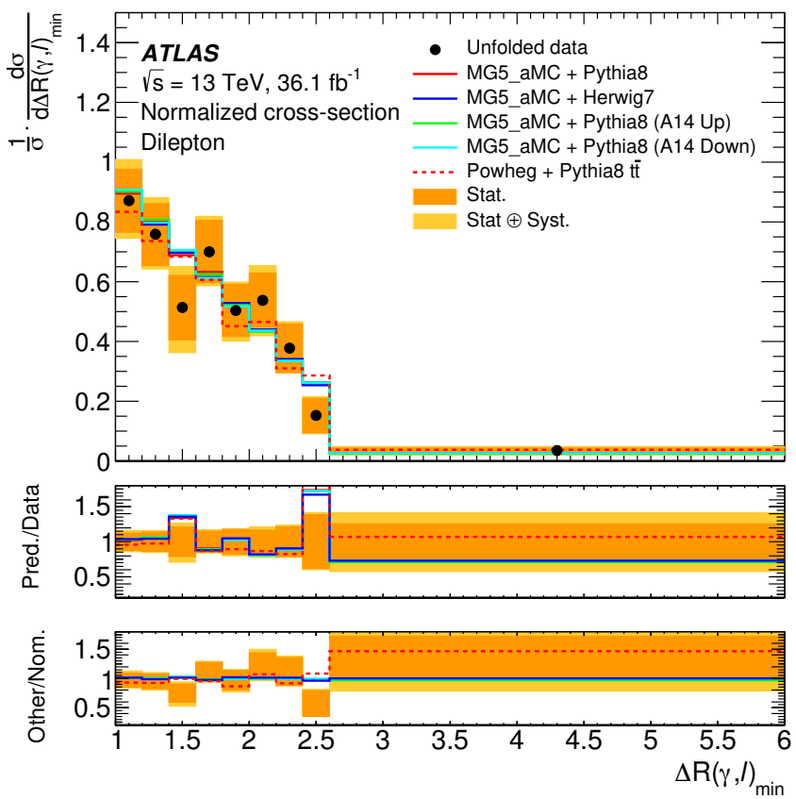
arXiv:1812.01697 (submitted to EPJC)

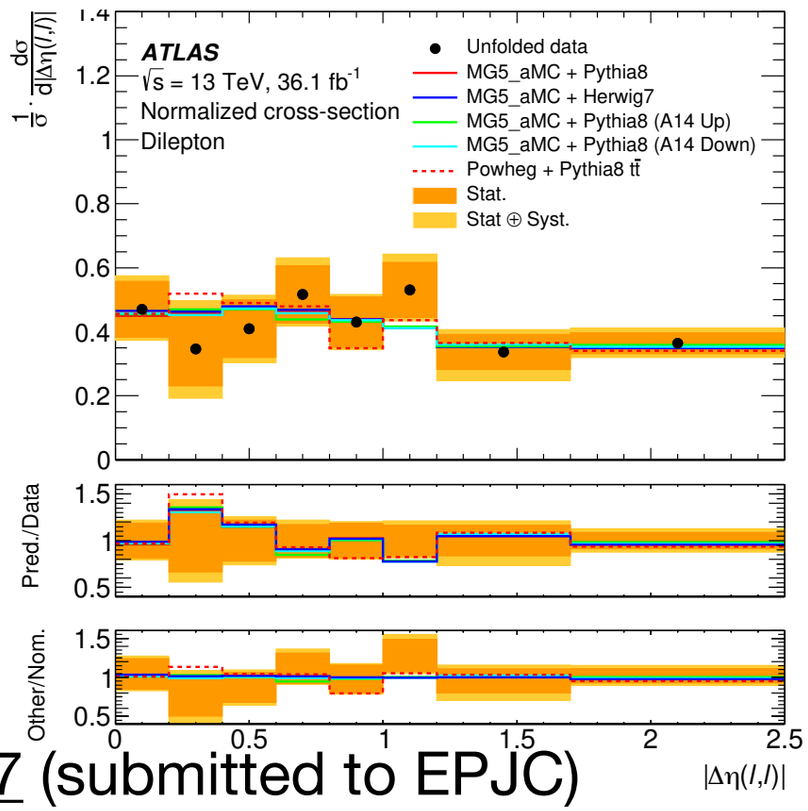
$t\bar{t}\gamma$ ATLAS

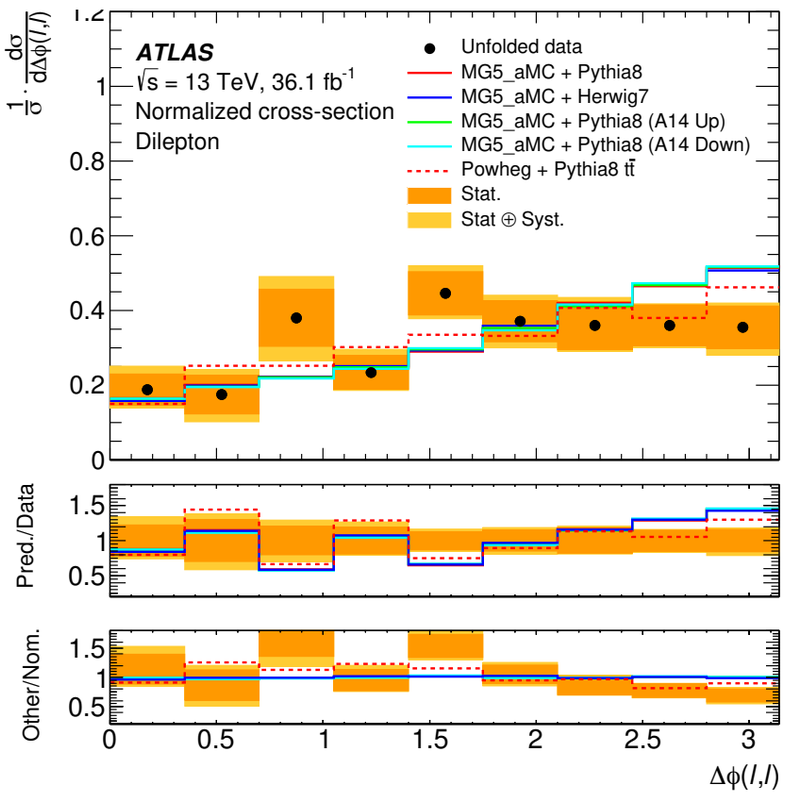
Differential cross section measurements in dilepton final state











arXiv:1812.01697 (submitted to EPJC)

tZq : ATLAS

Event selection
Signal, Control, and Validation Regions

Common selections			
Exactly 3 leptons with $\|\eta\| < 2.5$ and $p_{\mathrm{T}} > 15$ GeV $p_{\mathrm{T}}(\ell_1) > 28$ GeV, $p_{\mathrm{T}}(\ell_2) > 25$ GeV, $p_{\mathrm{T}}(\ell_3) > 15$ GeV $p_{\mathrm{T}}(\mathrm{jet}) > 30$ GeV $m_{\mathrm{T}}(\ell_W, \nu) > 20$ GeV			
SR	Diboson VR / CR	$t\bar{t}$ VR	$t\bar{t}$ CR
≥ 1 OSSF pair $\|m_{\ell\ell} - m_Z\| < 10$ GeV 2 jets, $\|\eta\| < 4.5$ 1 b-jet, $\|\eta\| < 2.5$ —	≥ 1 OSSF pair $\|m_{\ell\ell} - m_Z\| < 10$ GeV 1 jet, $\|\eta\| < 4.5$ — VR/CR: $m_{\mathrm{T}}(\ell_W, \nu) > 20/60$ GeV	≥ 1 OSSF pair $\|m_{\ell\ell} - m_Z\| > 10$ GeV 2 jets, $\|\eta\| < 4.5$ 1 b-jet, $\|\eta\| < 2.5$ —	≥ 1 OSDF pair No OSSF pair 2 jets, $\|\eta\| < 4.5$ 1 b-jet, $\|\eta\| < 2.5$ —

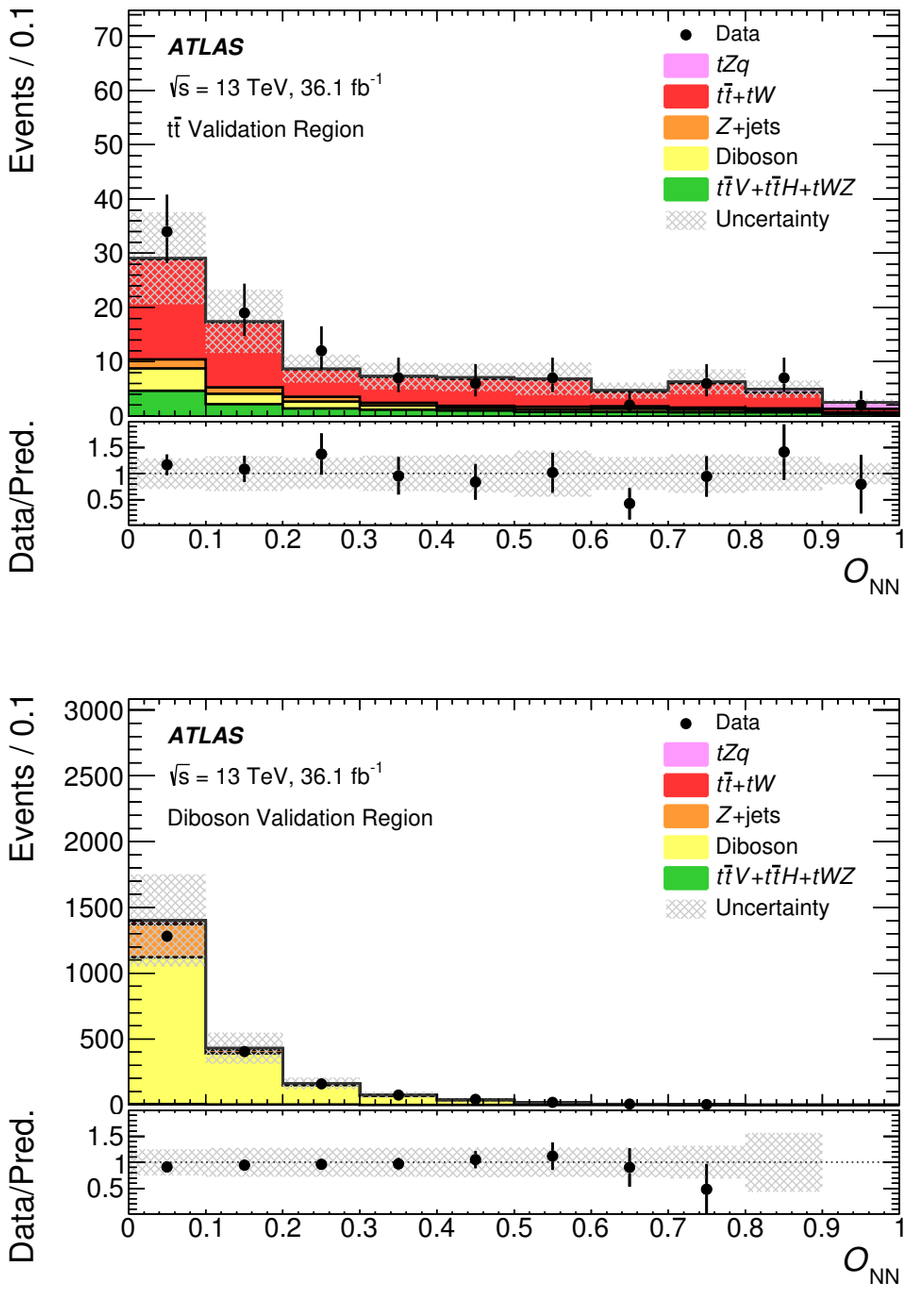
Phys. Lett. B 780 (2018) 557 (arXiv:1710.03659)

tZq : ATLAS

BDT Variables

Variable	Definition
$\|\eta(\mathrm{j})\|$	Absolute value of untagged jet η
$p_{\mathrm{T}}(\mathrm{j})$	Untagged jet p_{T}
m_t	Reconstructed top-quark mass
$p_{\mathrm{T}}(\ell^W)$	p_{T} of the lepton from the W-boson decay
$\Delta R(\mathrm{j}, Z)$	ΔR between the untagged jet and the Z boson
$m_{\mathrm{T}}(\ell, E_{\mathrm{T}}^{\mathrm{miss}})$	Transverse mass of W boson
$p_{\mathrm{T}}(t)$	Reconstructed top-quark p_{T}
$p_{\mathrm{T}}(b)$	Tagged jet p_{T}
$p_{\mathrm{T}}(Z)$	p_{T} of the reconstructed Z boson
$\|\eta(\ell^W)\|$	Absolute value of η of the lepton coming from the W-boson decay

BDT distribution in tt and Diboson validation regions

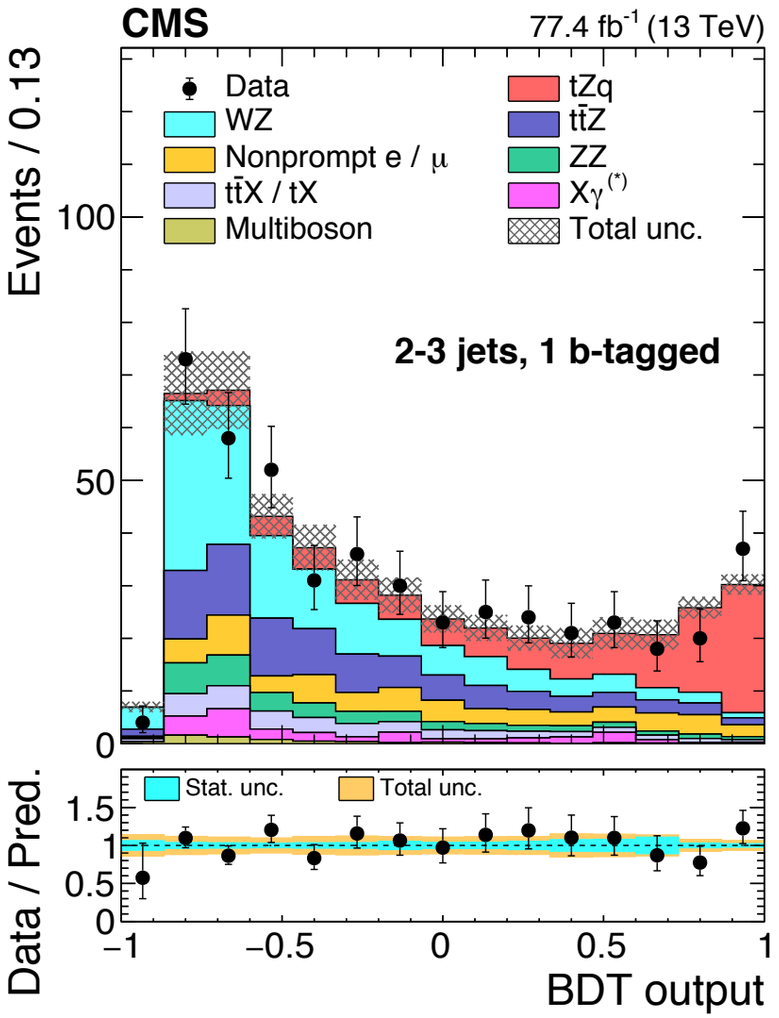


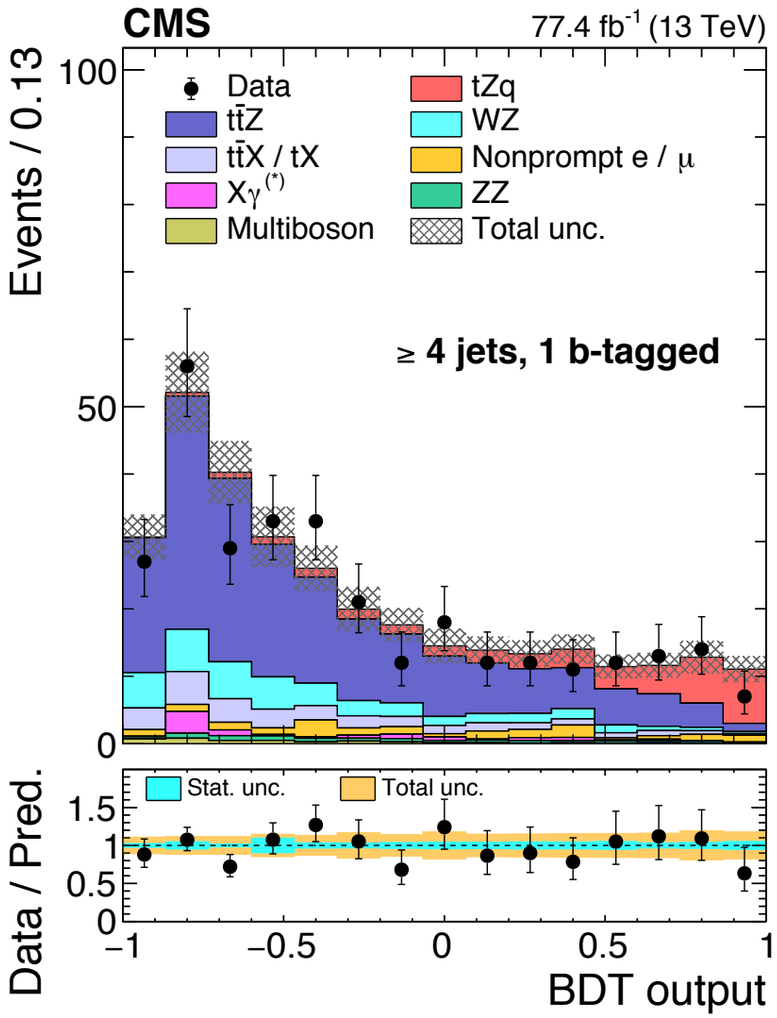
Phys. Lett. B 780 (2018) 557 (arXiv:1710.03659)

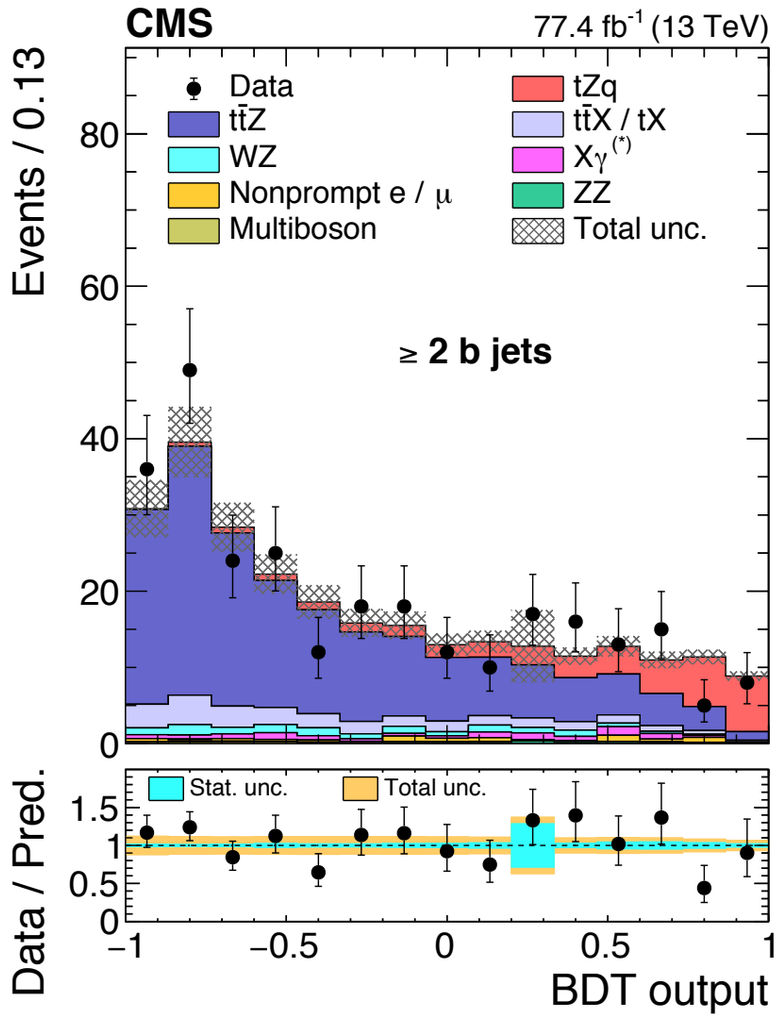
2016/17 Dataset
77.4 fb^{-1}

tZq CMS

- Dominant backgrounds from tt, z+jets,
- BDT trained on signal and backgrounds in each signal region
  - eg: |η| of recoiling jet, max m_{jj}, W transverse mass
- Largest systematics by non prompt modeling and lepton eff.





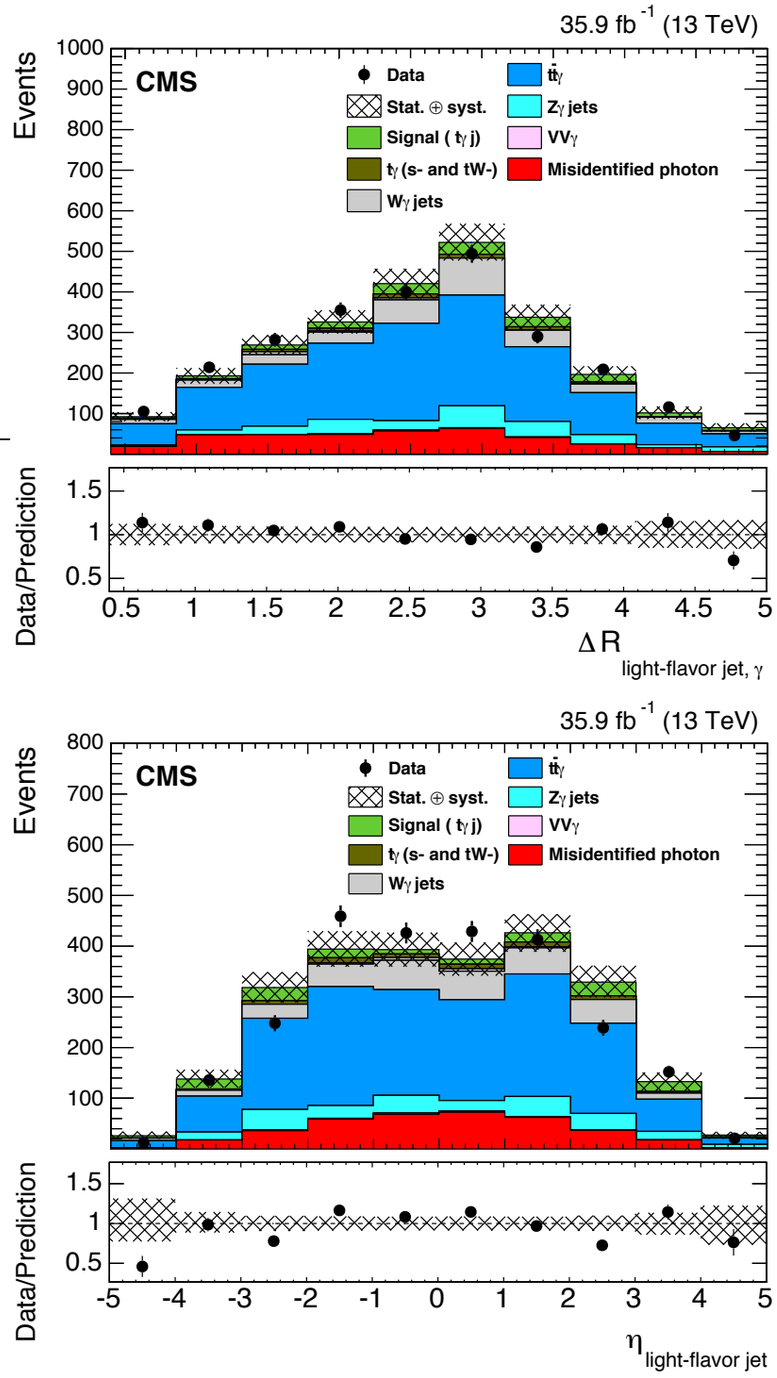


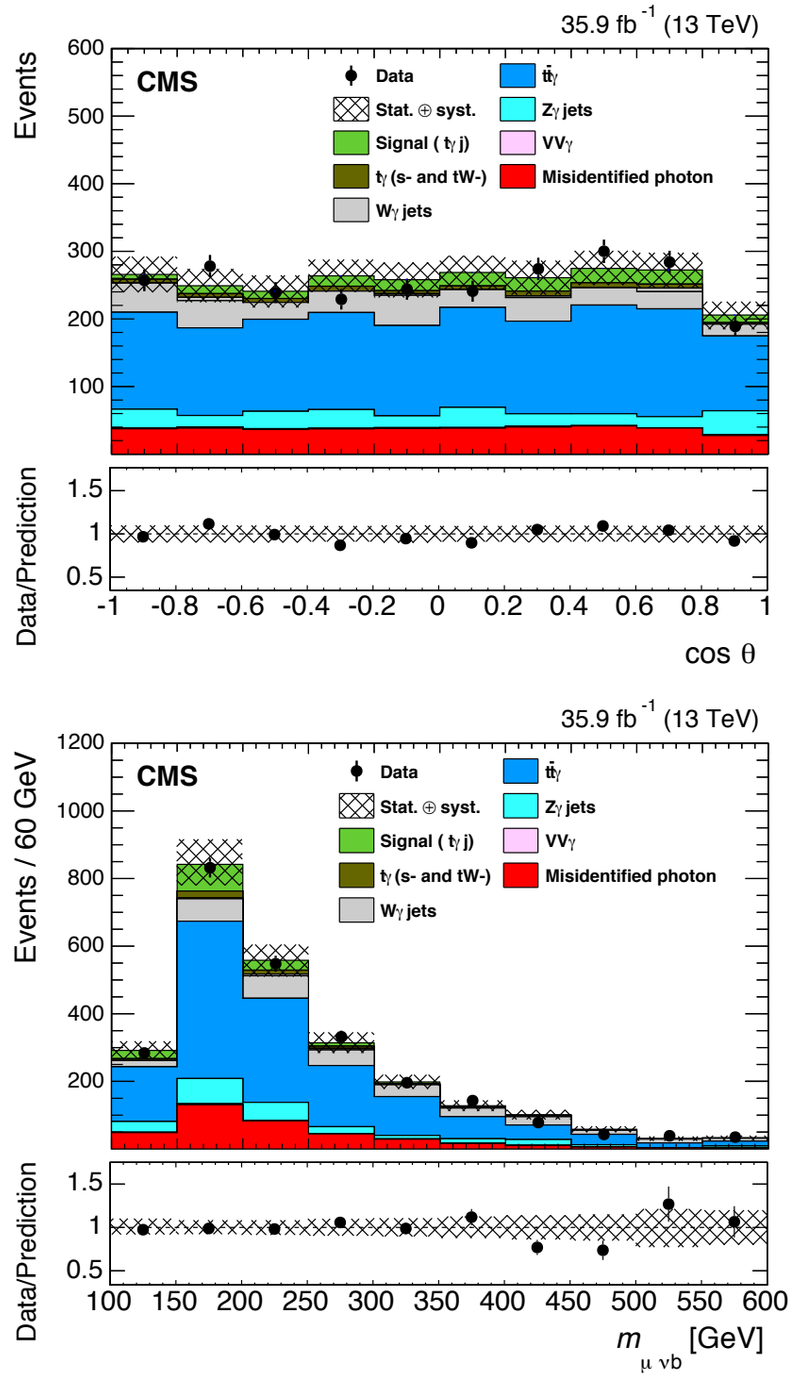
arXiv:1812.05900 (accepted by PRL)

2016 Dataset
35.9 fb^{-1}

Evidence of tγ CMS

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





arXiv:1812.05900 (accepted by PRL)

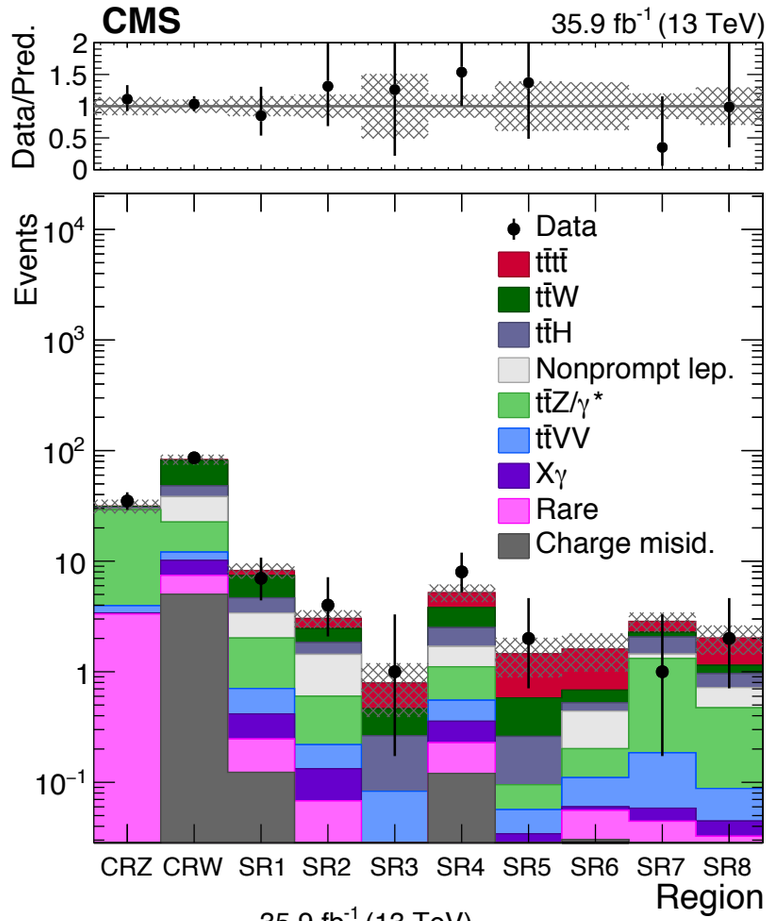
2016 Dataset
35.9 fb^{-1}

Four top CMS

SS Dilepton & Multilepton

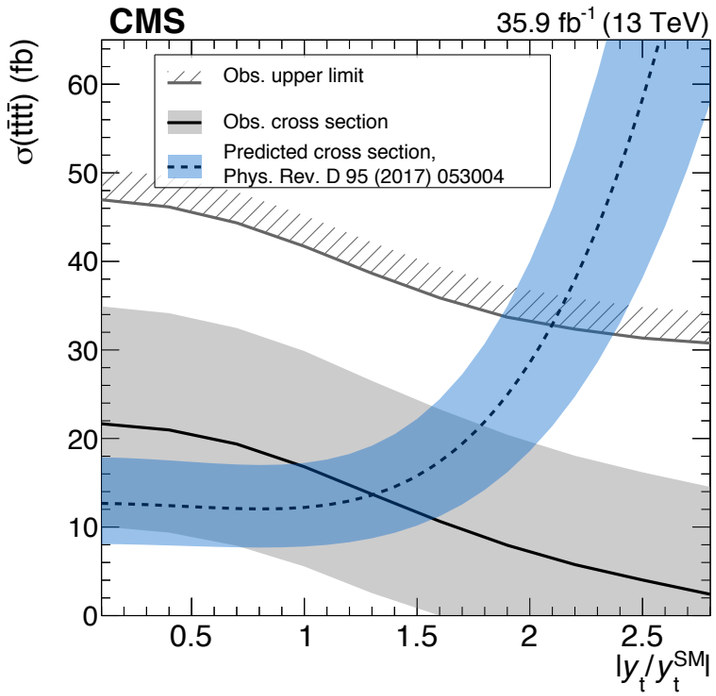
- Measurement in multilepton final states (SS dilepton & ≥3 lepton)
- Signal and control regions defined in jet/bjet multiplicity bins
  - ttW / ttZ backgrounds taken from simulation, with control regions to verify yields
  - Nonprompt lepton background estimated from data
- Simultaneous fit to event yields in all regions
- Limits placed on top yukawa coupling

N_ℓ	N_b	N_{jets}	Region
2	2	≤5	CRW
		6	SR1
		7	SR2
		≥8	SR3
	3	5, 6	SR4
		≥7	SR5
	≥4	≥5	SR6
≥3	2	≥5	SR7
	≥3	≥4	SR8
Inverted Z veto			CRZ



$$\sigma^{\text{meas.}}(\text{pp} \to \text{t}\bar{\text{t}}\text{t}\bar{\text{t}}) = 16.9^{+13.8}_{-11.4}\ \text{fb}$$
$$\sigma^{\text{th.}}(\text{pp} \to \text{t}\bar{\text{t}}\text{t}\bar{\text{t}}) = 9.2^{+2.9}_{-2.4}\ \text{fb}$$

95% CL upper limit of 41.7 fb

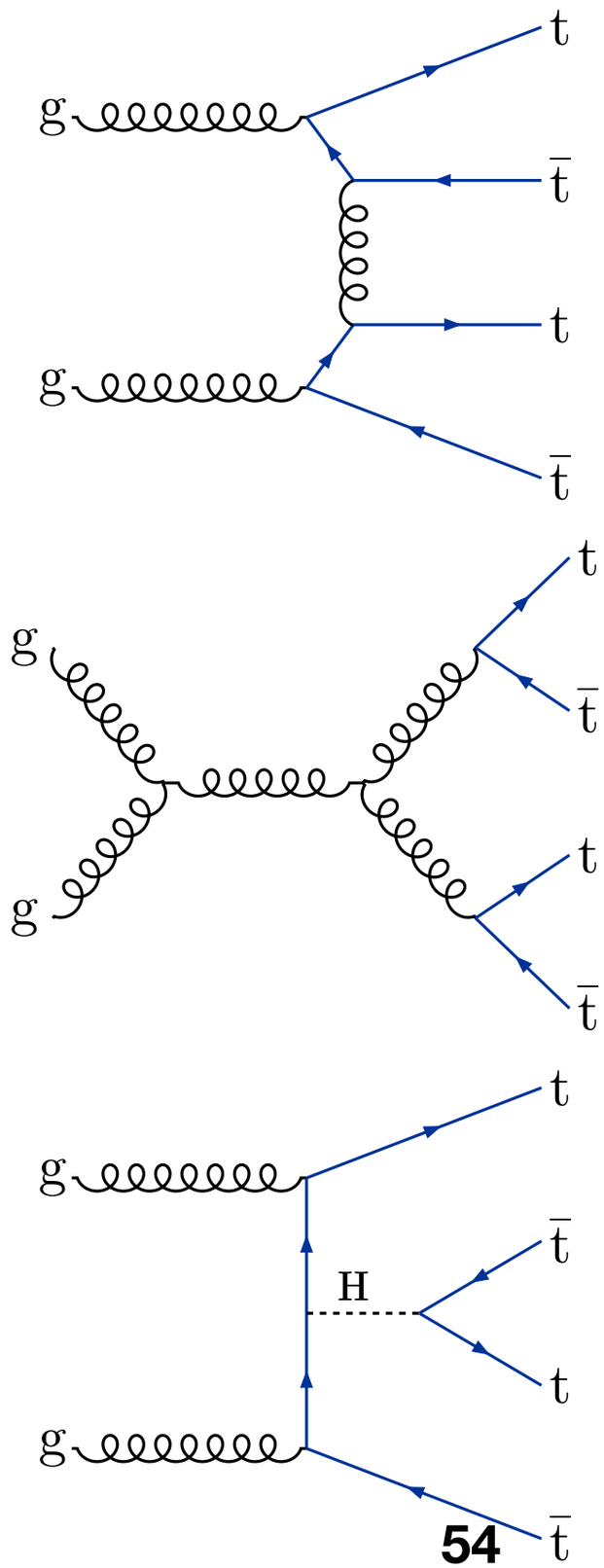


Eur. Phys. J. C 78 (2018) 140 (arXiv:1710.10614)

Four top : CMS

SS Dilepton & Multilepton

- Measured in same-sign dilepton and 3+ lepton final states
- Selection requires ≥2 jets, ≥2 b-jets, H_T>300 GeV, and p_T^{miss} > 50 GeV
- Define signal regions based on lepton, jet, and b-jet multiplicities



	SM background	$t\bar{t}t\bar{t}$	Total	Observed
CRZ	31.7 ± 4.6	0.4 ± 0.3	32.1 ± 4.6	35
CRW	83.7 ± 8.8	1.9 ± 1.2	85.6 ± 8.6	86
SR1	7.7 ± 1.2	0.9 ± 0.6	8.6 ± 1.2	7
SR2	2.6 ± 0.5	0.6 ± 0.4	3.2 ± 0.6	4
SR3	0.5 ± 0.3	0.4 ± 0.2	0.8 ± 0.4	1
SR4	4.0 ± 0.7	1.4 ± 0.9	5.4 ± 0.9	8
SR5	0.7 ± 0.2	0.9 ± 0.6	1.6 ± 0.6	2
SR6	0.7 ± 0.2	1.0 ± 0.6	1.7 ± 0.6	0
SR7	2.3 ± 0.5	0.6 ± 0.4	2.9 ± 0.6	1
SR8	1.2 ± 0.3	0.9 ± 0.6	2.1 ± 0.6	2

N_ℓ	N_b	N_{jets}	Region
2	2	≤5	CRW
		6	SR1
		7	SR2
		≥8	SR3
	3	5, 6	SR4
		≥7	SR5
	≥4	≥5	SR6
≥3	2	≥5	SR7
	≥3	≥4	SR8
Inverted Z veto			CRZ

Eur. Phys. J. C 78 (2018) 140 (arXiv:1710.10614)

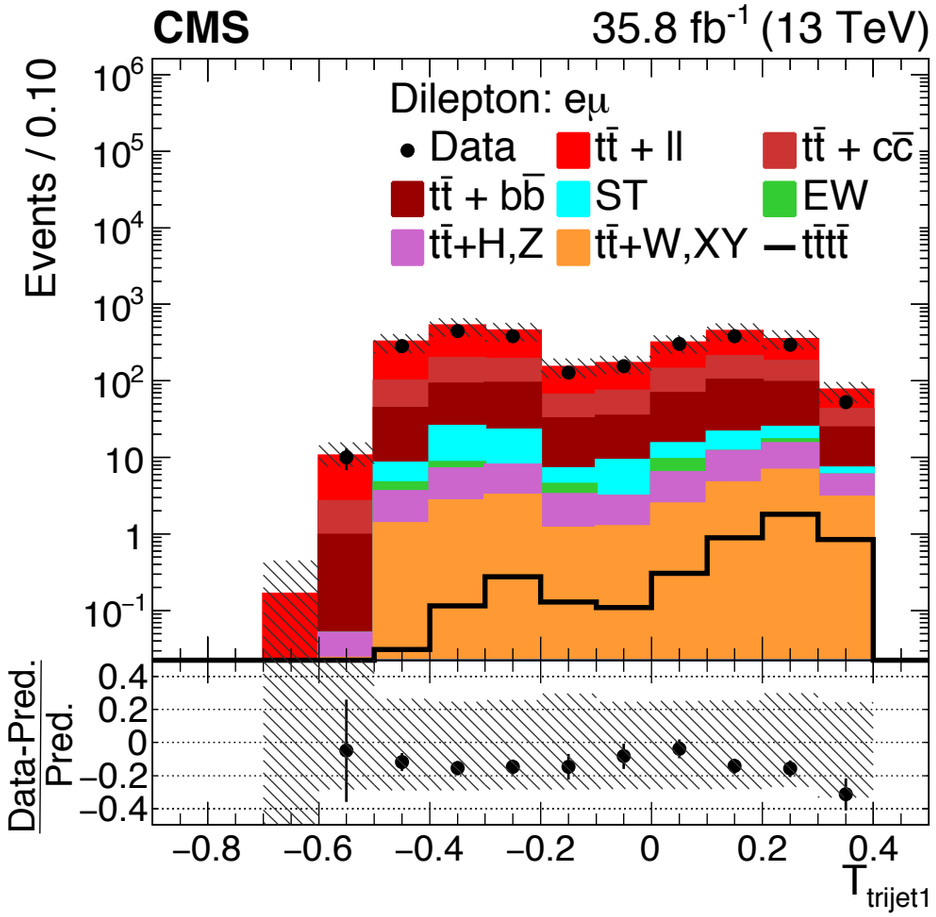
2016 Dataset
35.9 fb^{-1}

Four top CMS

Single Lepton & OS Dilepton

- BDT to reconstruct trijet combinations likely coming from
  - All jet permutations considered, ordered by decreasing discriminant value
  - $T_{trijet1}$ discriminant for leading combination
  - $T_{trijet2}$ discriminant for subleading combination (after removing permutations including jets in $T_{trijet1}$ combination)
- In dilepton top pair background, no hadronic tops expected, so $T_{trijet1}$ is used to discriminate
- In single lepton top pair background, exactly one hadronically decaying top expected, so $T_{trijet2}$ is used to discriminate

- Input variables
  - dijet masses
  - trijet masses
  - b-tagging information
  - angles between 3 jets



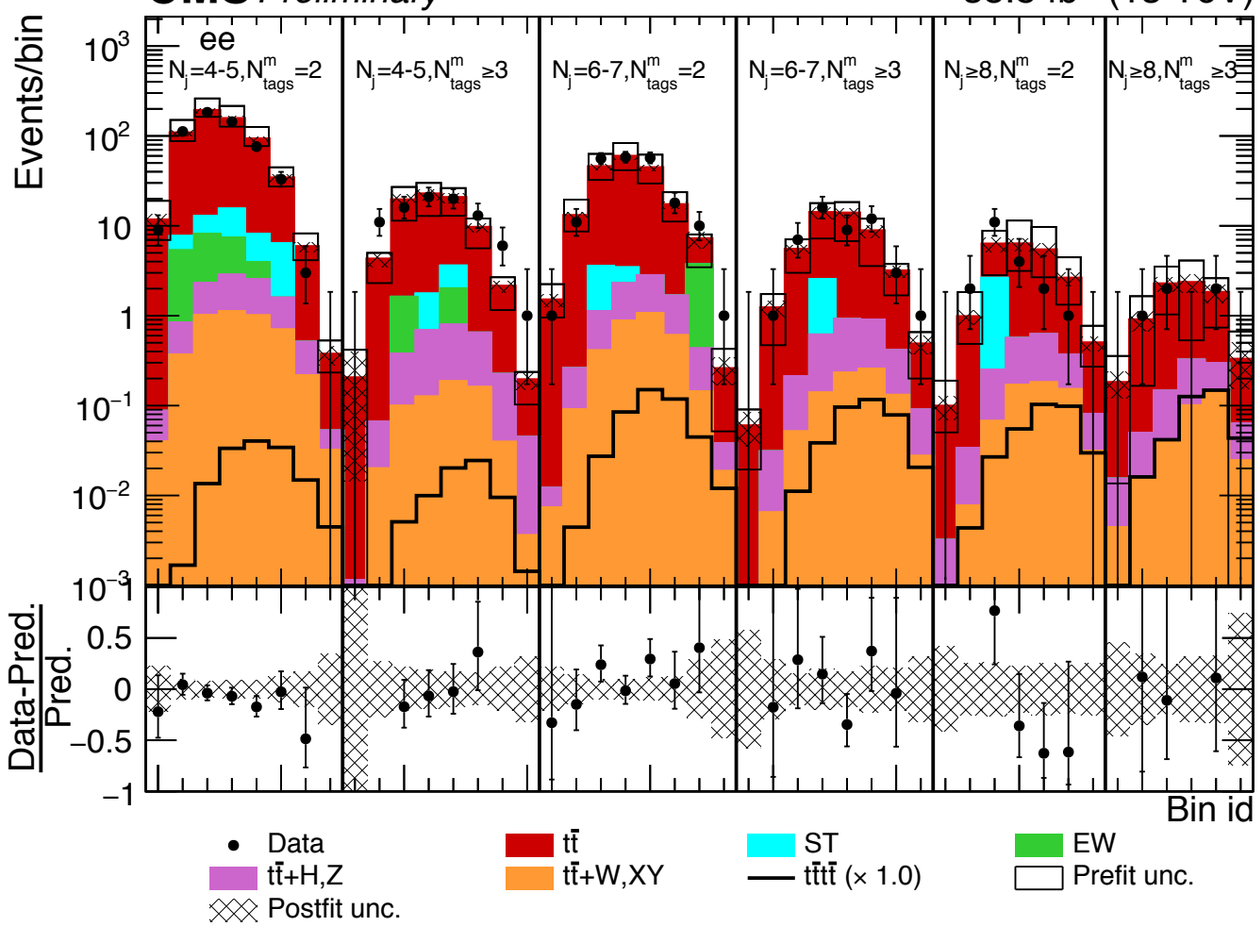
CMS PAS TOP-17-019

2016 Dataset
35.9 fb^{-1}

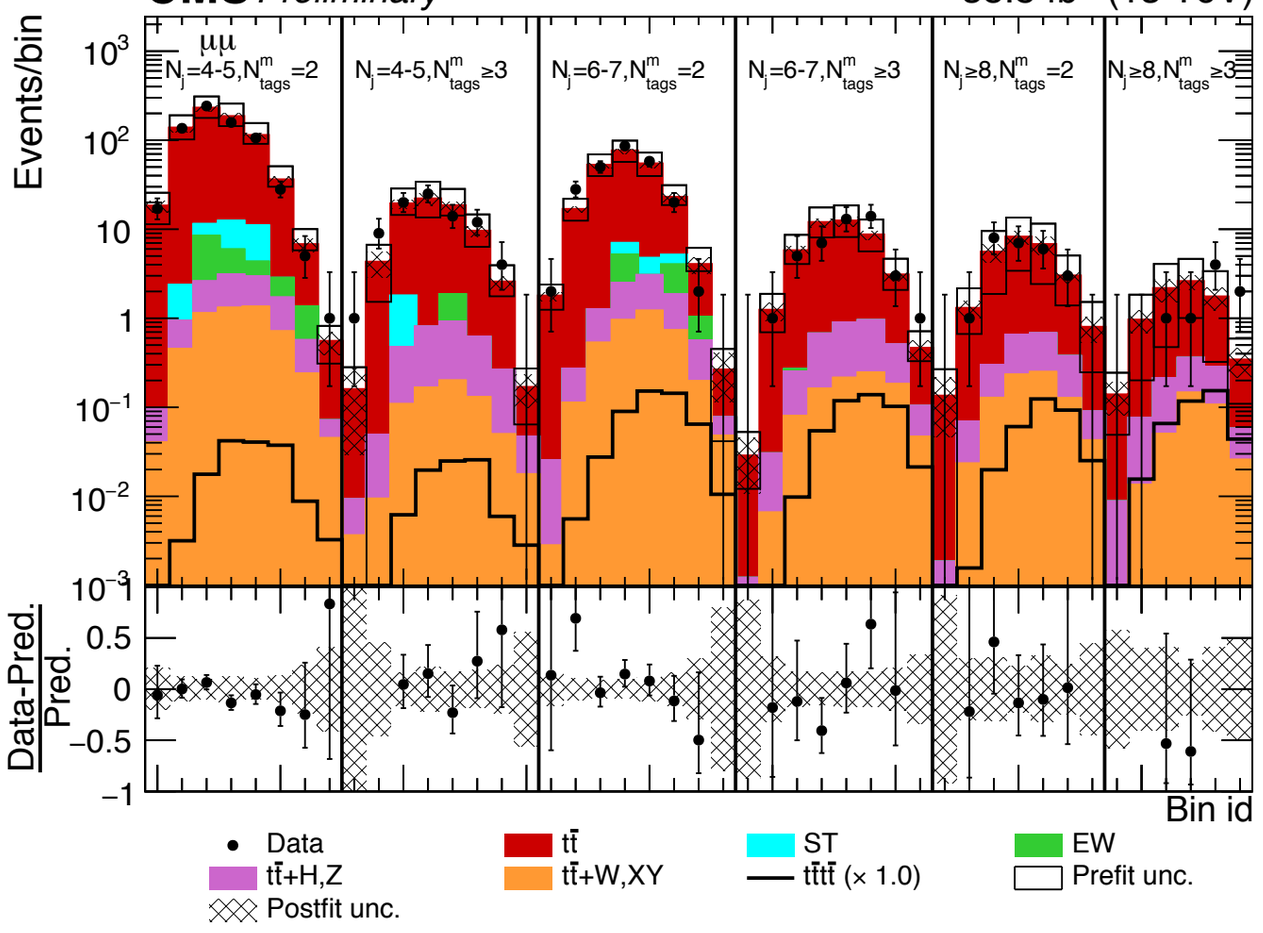
Four top CMS

Single Lepton & OS Dilepton

BDT Distribution in ee final state



BDT Distribution in μμ final state



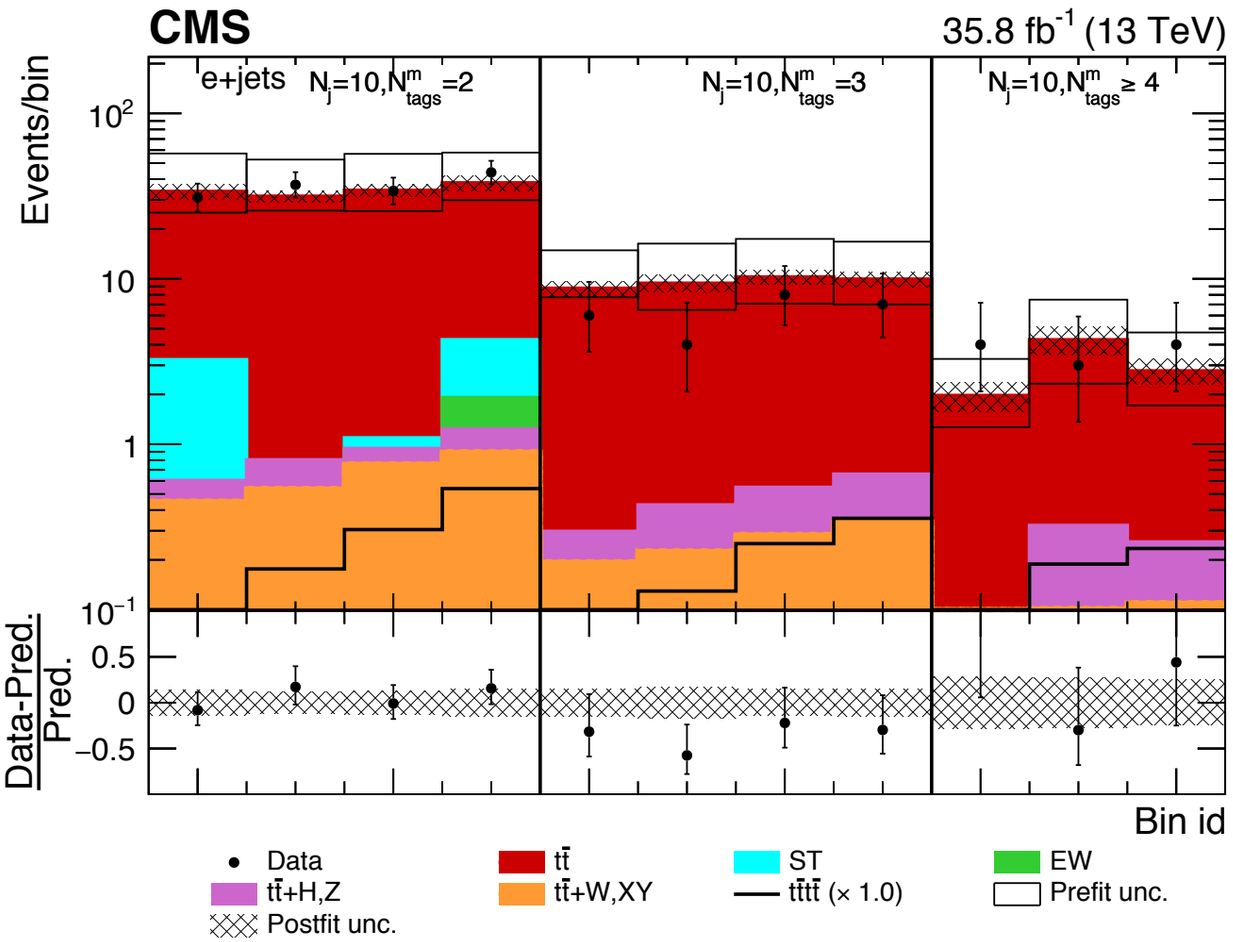
CMS PAS TOP-17-019

2016 Dataset
35.9 fb^{-1}

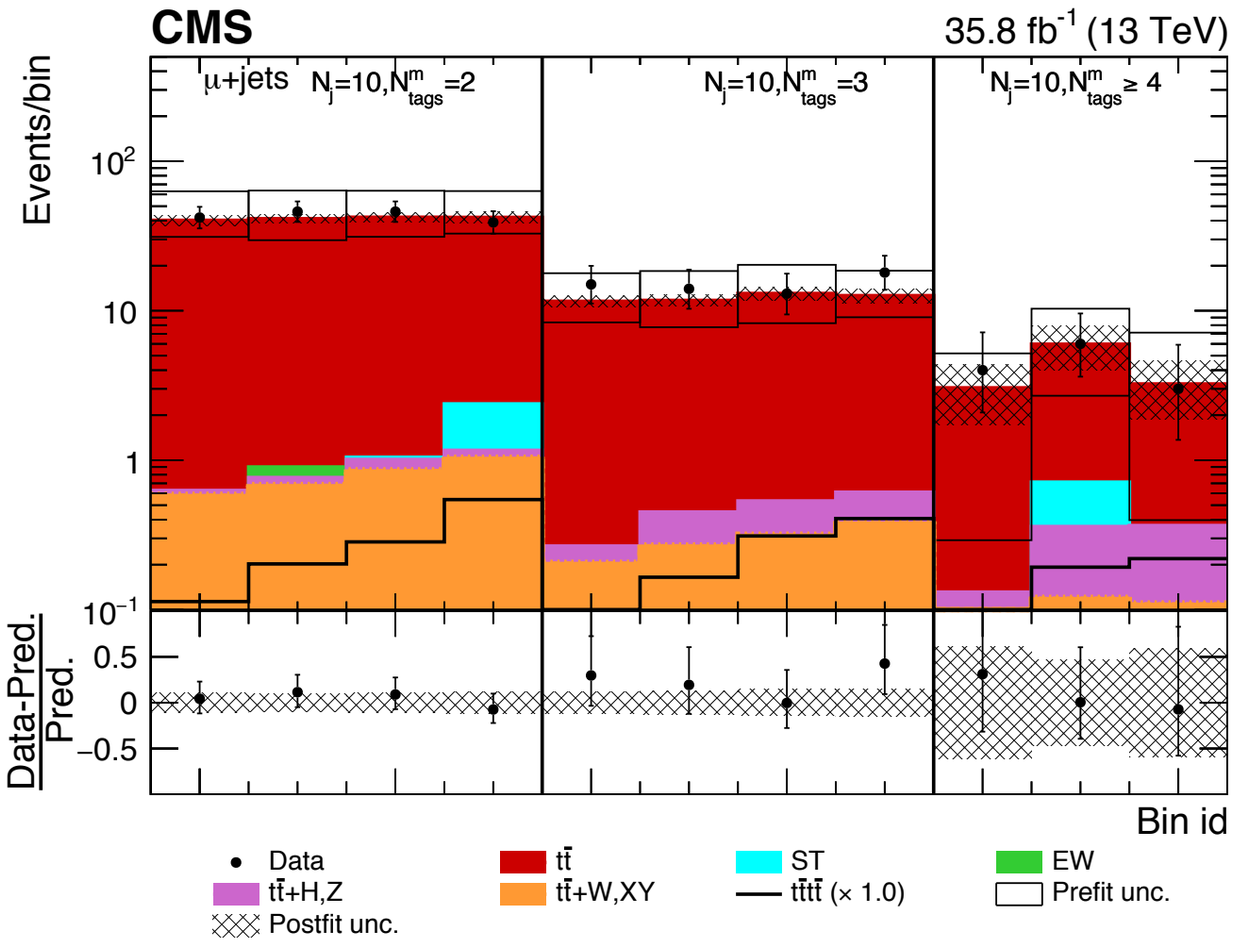
Four top CMS

Single Lepton & OS Dilepton

BDT Distribution in e+jets final state



BDT Distribution in μ+jets final state



CMS PAS TOP-17-019

2016 Dataset
35.9 fb^{-1}

Four top CMS

Single Lepton & OS Dilepton

EFT Limits

$$\sigma_{\mathrm{t\bar{t}t\bar{t}}} = \sigma^{\mathrm{SM}}_{\mathrm{t\bar{t}t\bar{t}}} + \frac{1}{\Lambda^2}\sum_k C_k \sigma_k^{(1)} + \frac{1}{\Lambda^4}\sum_{j\leq k} C_j C_k \sigma_{j,k}^{(2)}$$

Dim-6 operators

$$\begin{aligned}
\mathcal{O}^1_{tt} &= (\bar{t}_R\gamma^\mu t_R)(\bar{t}_R\gamma_\mu t_R)\\
\mathcal{O}^1_{QQ} &= (\bar{Q}_L\gamma^\mu Q_L)(\bar{Q}_L\gamma_\mu Q_L)\\
\mathcal{O}^1_{Qt} &= (\bar{Q}_L\gamma^\mu Q_L)(\bar{t}_R\gamma_\mu t_R)\\
\mathcal{O}^8_{Qt} &= (\bar{Q}_L\gamma^\mu T^A Q_L)(\bar{t}_R\gamma_\mu T^A t_R)
\end{aligned}$$

Cross section contributions

Operator	$\sigma_k^{(1)}$
$\mathcal{O}^1_{tt}$	0.39
$\mathcal{O}^1_{QQ}$	0.47
$\mathcal{O}^1_{Qt}$	0.03
$\mathcal{O}^8_{Qt}$	0.28

Operator	$\mathcal{O}^1_{tt}$	$\mathcal{O}^1_{QQ}$	$\mathcal{O}^1_{Qt}$	$\mathcal{O}^8_{Qt}$
$\mathcal{O}^1_{tt}$	5.59	0.36	−0.39	0.3
$\mathcal{O}^1_{QQ}$		5.49	−0.45	0.13
$\mathcal{O}^1_{Qt}$			1.9	−0.08
$\mathcal{O}^8_{Qt}$				0.45

Expected and observed limits

	Expected	Observed
Operator	C_k/Λ^2 (TeV^{-2})	C_k/Λ^2(TeV^{-2})
$\mathcal{O}^1_{tt}$	$[-1.5, 1.3]$	$[-2.1, 2.0]$
$\mathcal{O}^1_{QQ}$	$[-1.5, 1.3]$	$[-2.2, 2.0]$
$\mathcal{O}^1_{Qt}$	$[-2.4, 2.4]$	$[-3.5, 3.5]$
$\mathcal{O}^8_{Qt}$	$[-5.6, 4.3]$	$[-7.9, 6.6]$

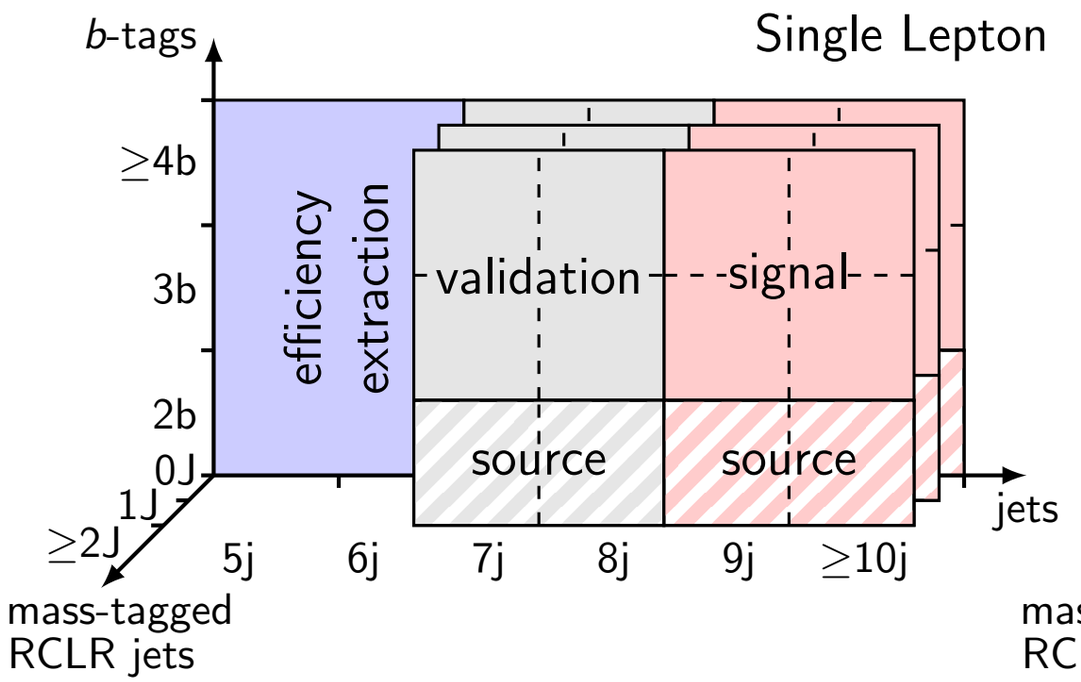
CMS PAS TOP-17-019

Four top : ATLAS

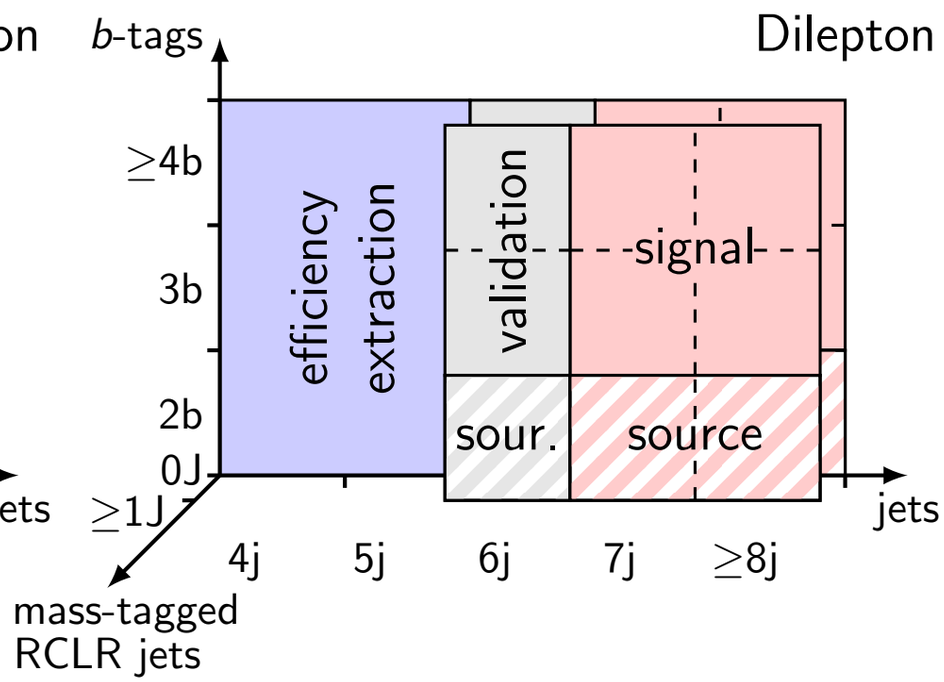
Single Lepton & OS Dilepton

Preselection requirements		
Requirement	Single-lepton	Dilepton
Trigger	Single-lepton triggers	
Leptons	1 isolated	2 isolated, opposite-sign
Jets	$\geq$5 jets	$\geq$4 jets
b-tagged jets	$\geq$2 b-tagged jets	
Other	$E_{\mathrm{T}}^{\mathrm{miss}} > 20$ GeV	$m_{\ell\ell} > 50$ GeV
	$E_{\mathrm{T}}^{\mathrm{miss}} + m_{\mathrm{T}}^{W} > 60$ GeV	$\lvert m_{\ell\ell} - 91\ \mathrm{GeV}\rvert > 8$ GeV

Reclustered R=1.0 Jets
$p_{\mathrm{T}} > 200$ GeV
$\lvert\eta\rvert < 2.0$
mass > 100 GeV
≥ 1 R=0.4 jet



Single Lepton

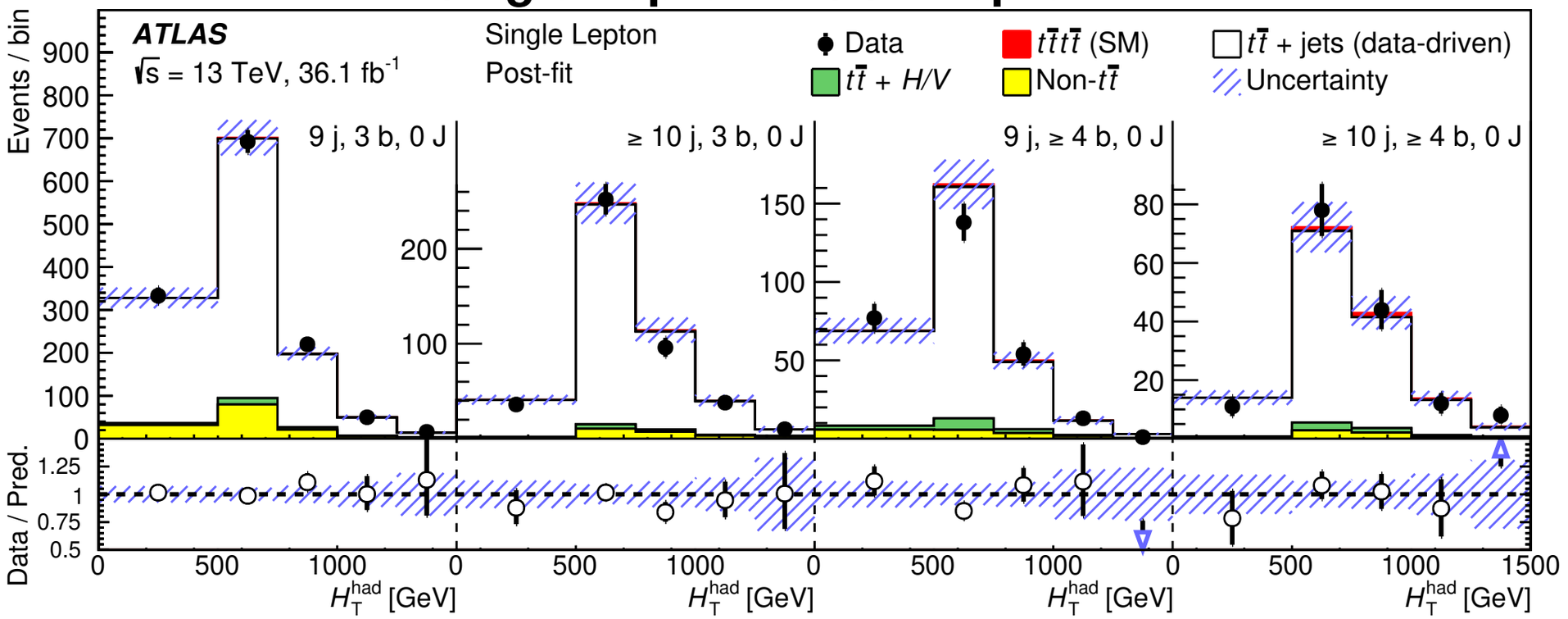


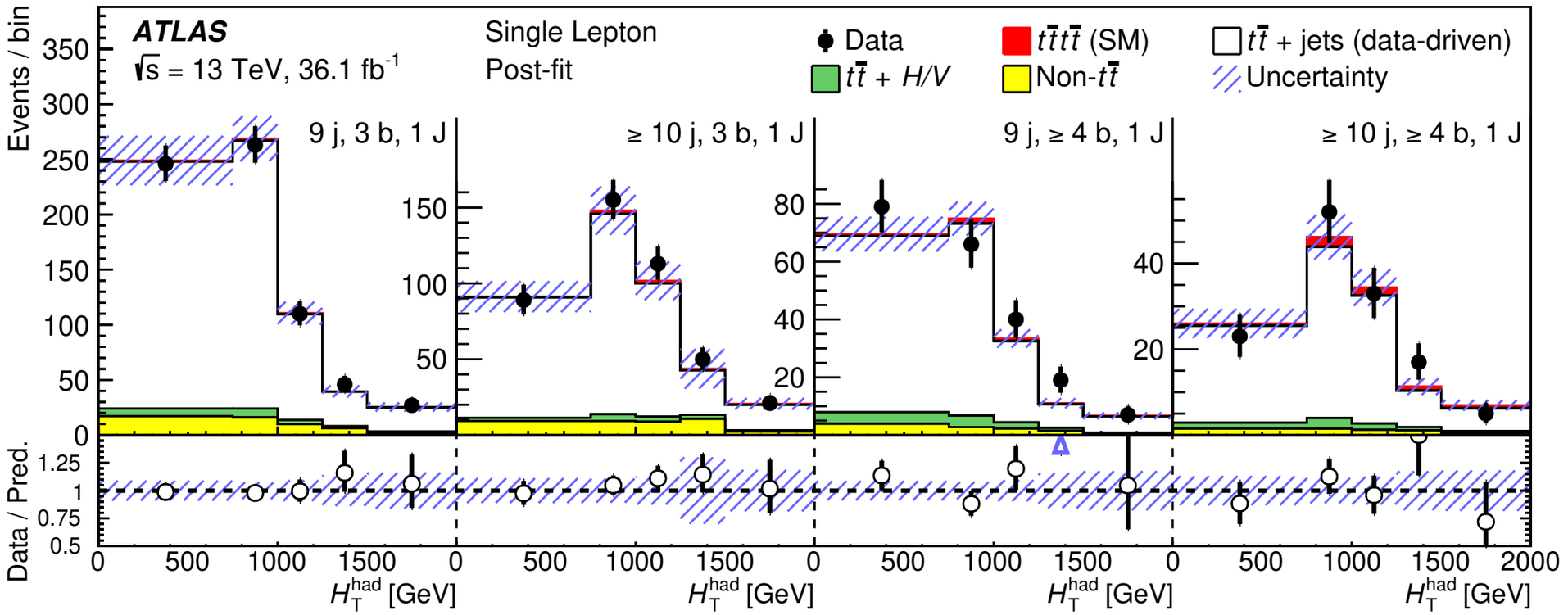
Dilepton

arXiv:1811.02305, submitted to Phys. Rev. D

Four top : ATLAS

Single Lepton & OS Dilepton

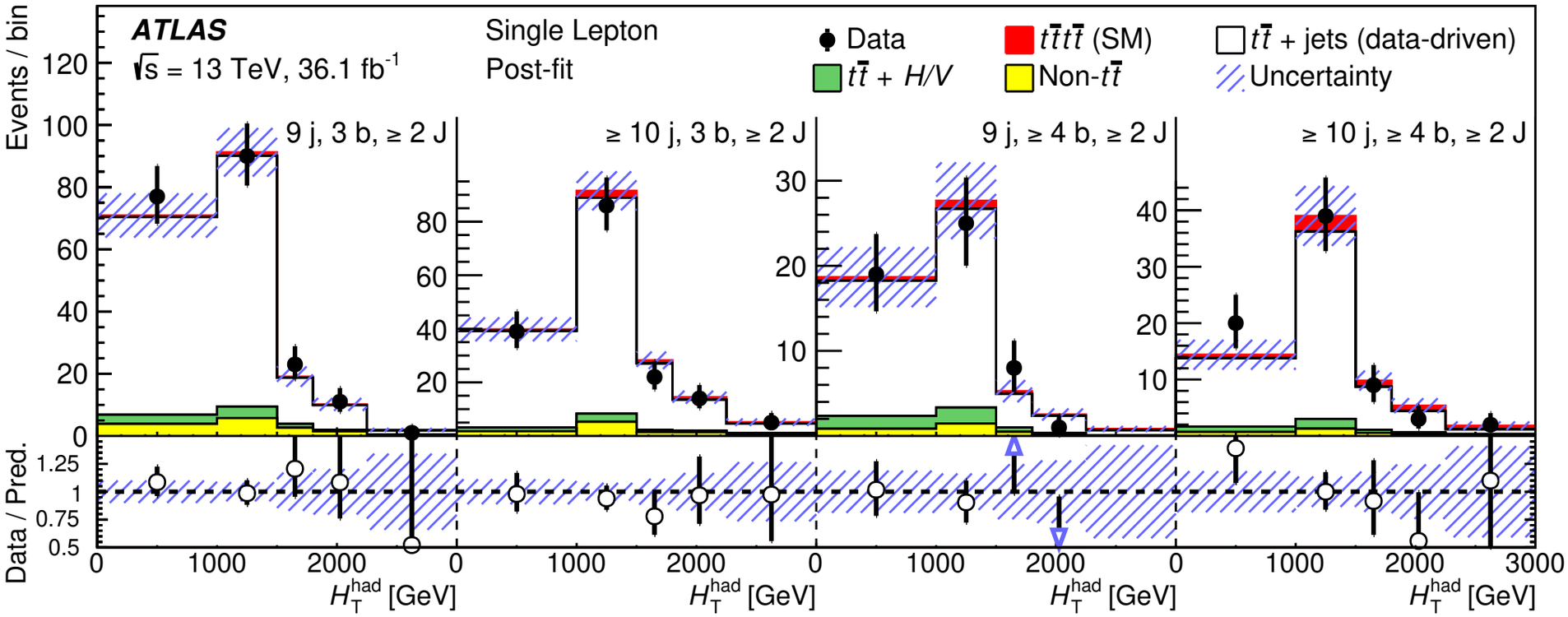




arXiv:1811.02305, submitted to Phys. Rev. D

Four top : ATLAS

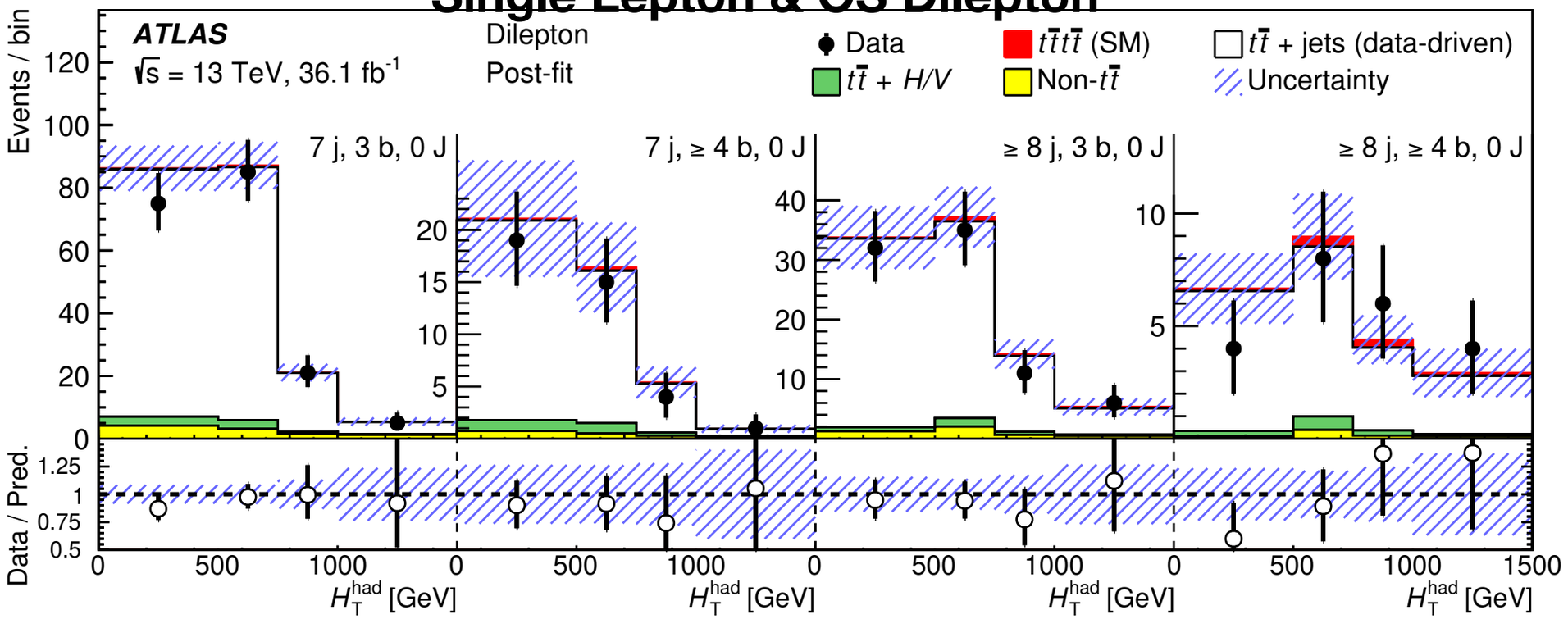
Single Lepton & OS Dilepton

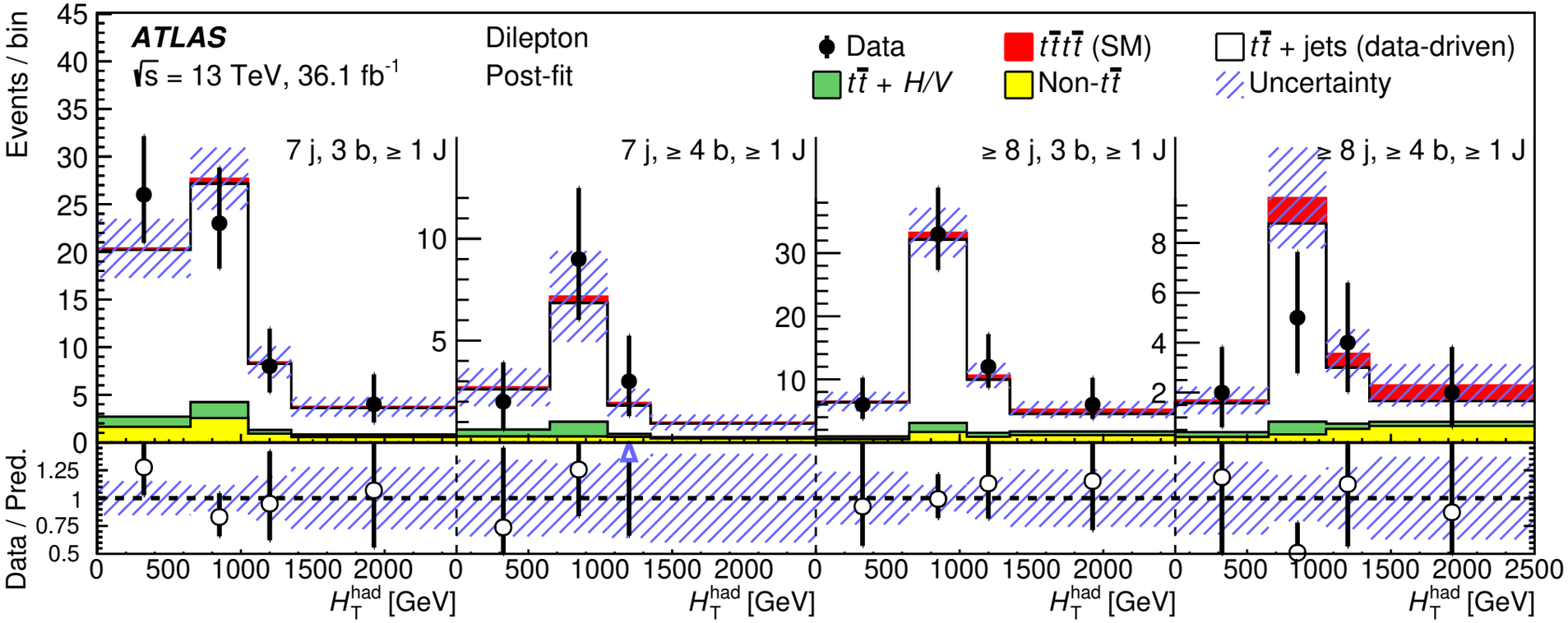


arXiv:1811.02305, submitted to Phys. Rev. D

Four top : ATLAS

Single Lepton & OS Dilepton

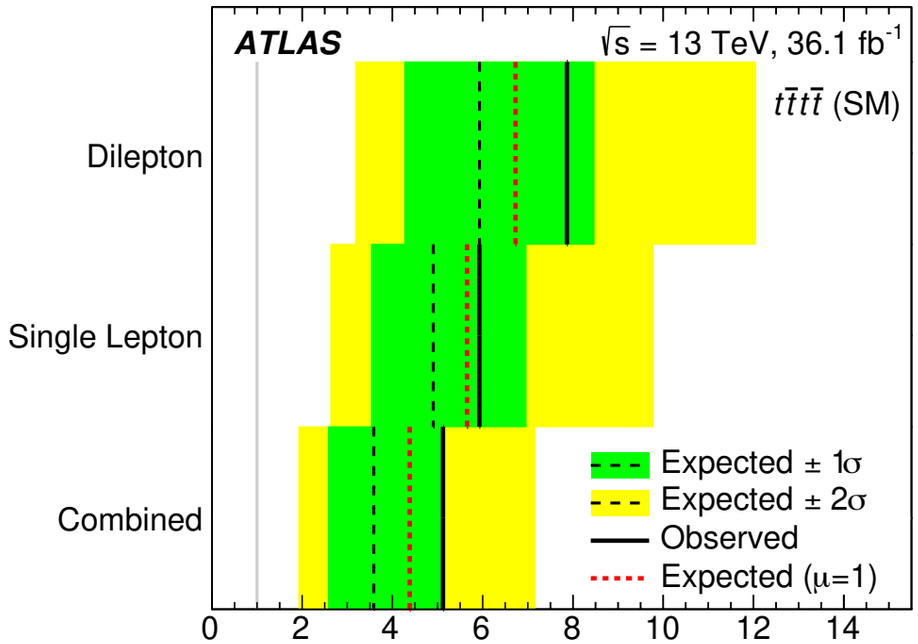


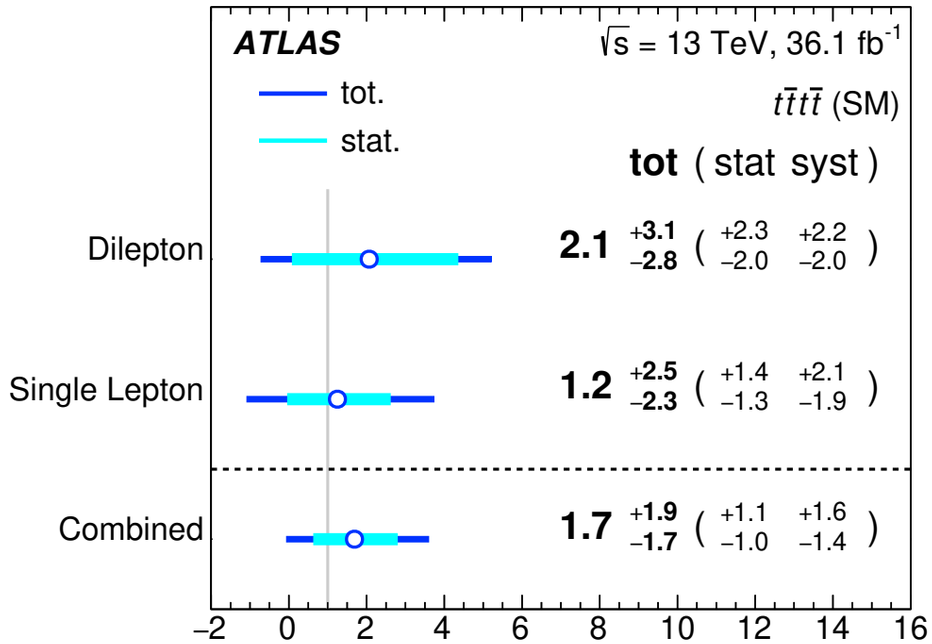


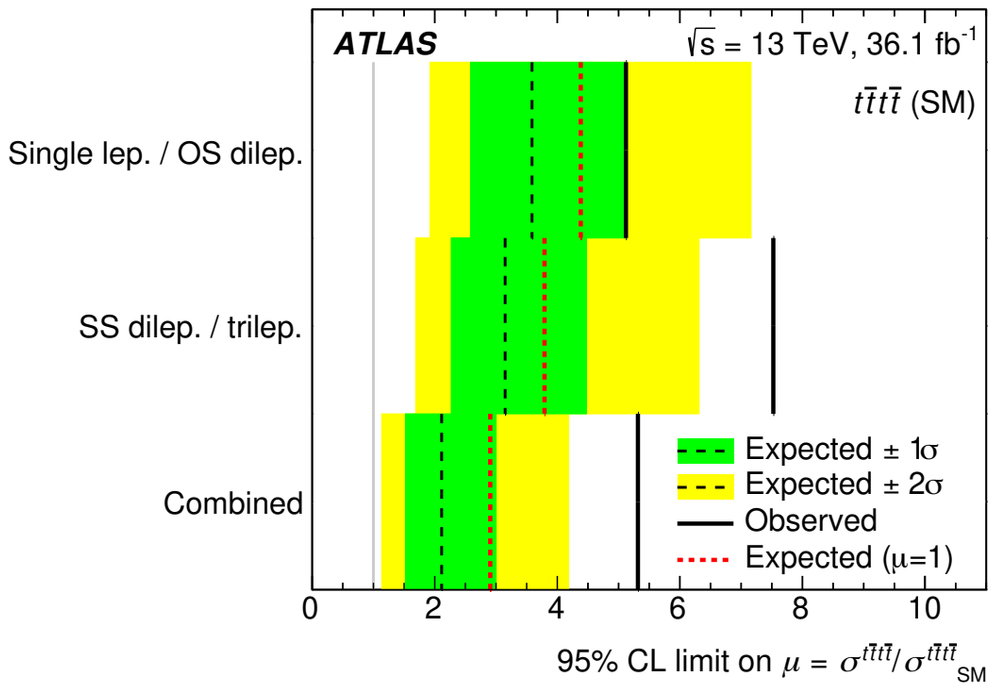
arXiv:1811.02305, submitted to Phys. Rev. D

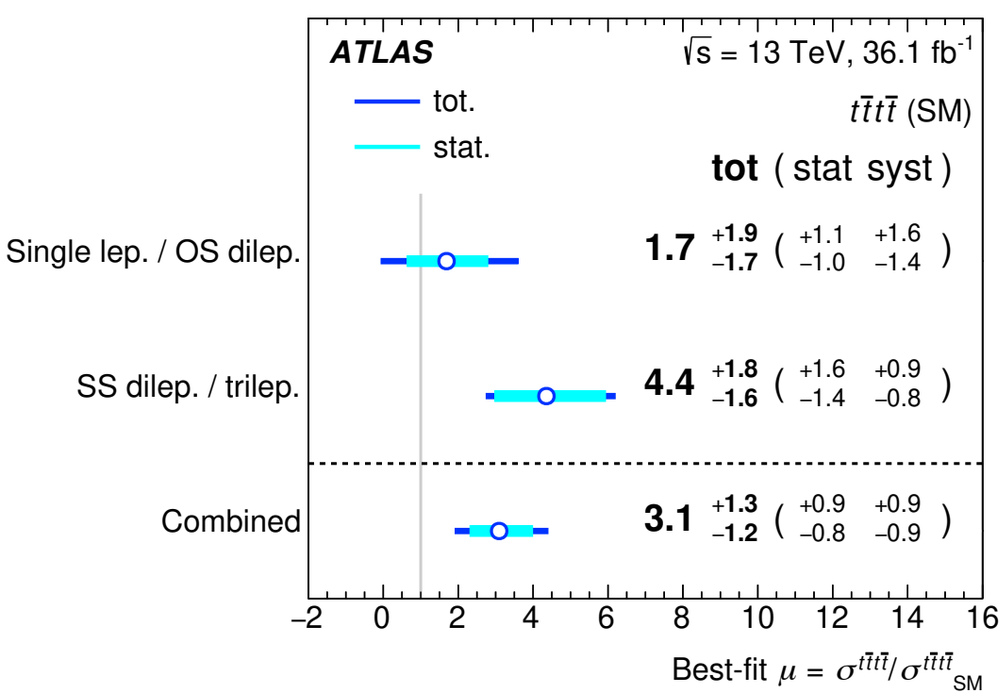
Four top : ATLAS

Single Lepton & OS Dilepton







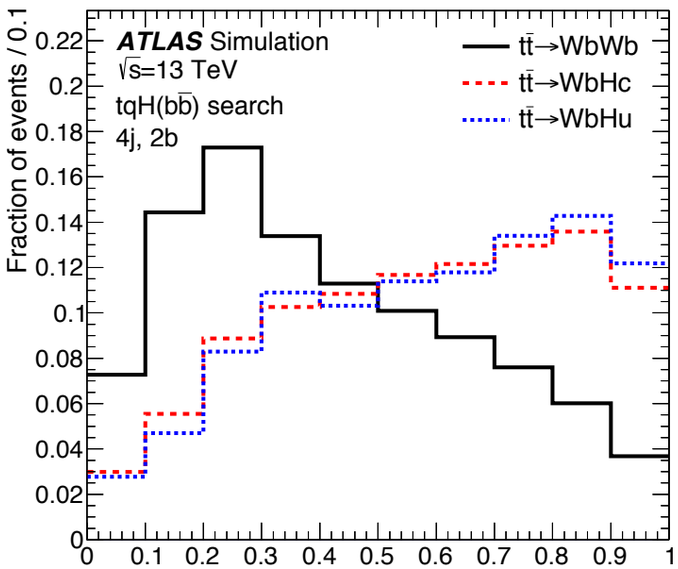


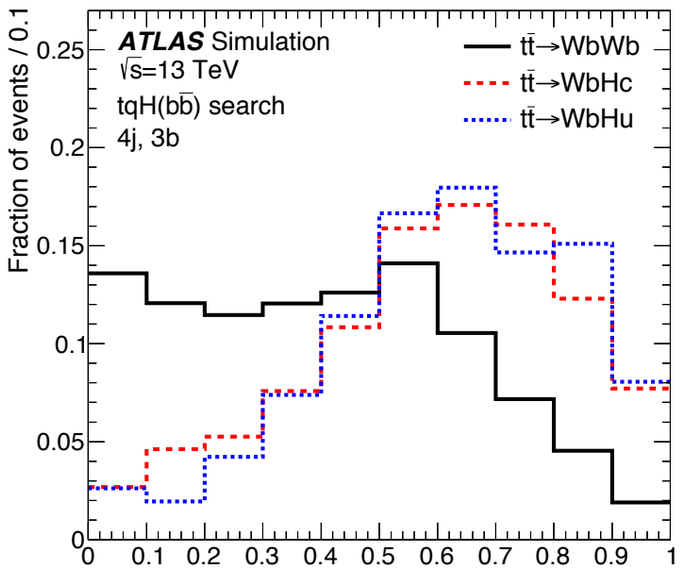
arXiv:1811.02305, submitted to Phys. Rev. D

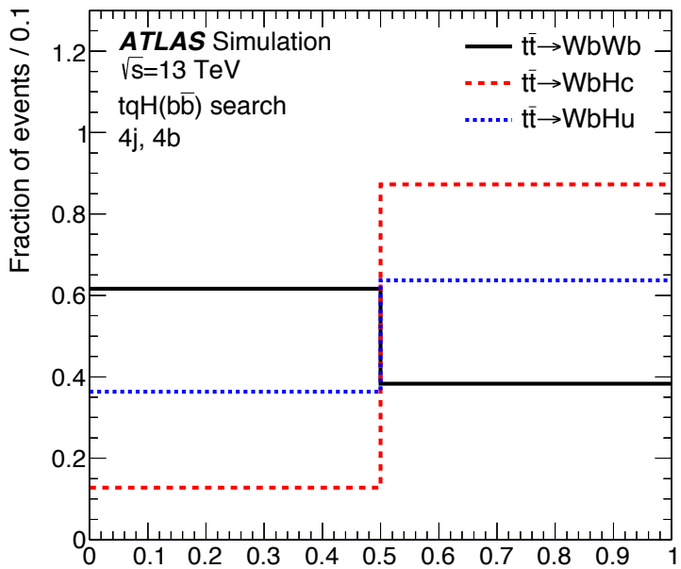
2015/16 Dataset
36.1 fb^{-1}

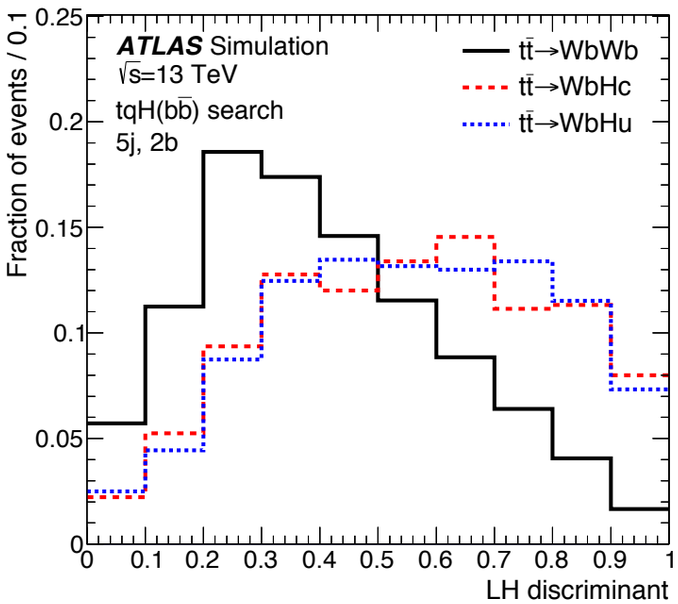
FCNC tHq ATLAS

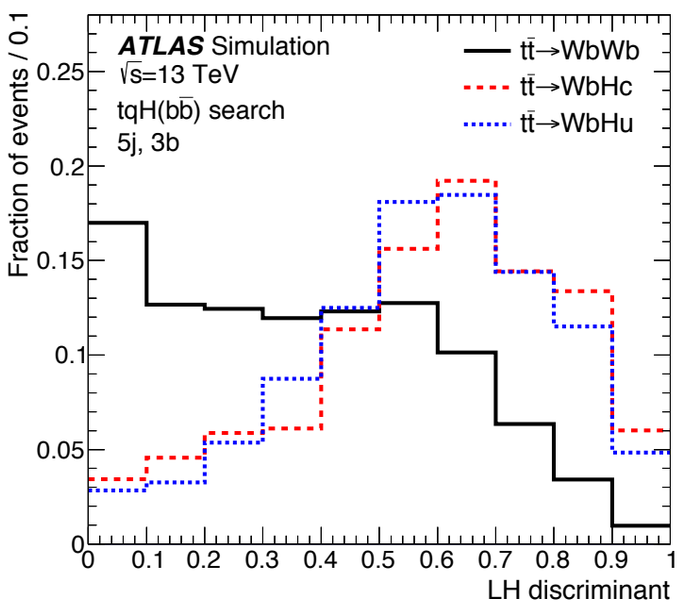
H->bb likelihood discriminant shapes

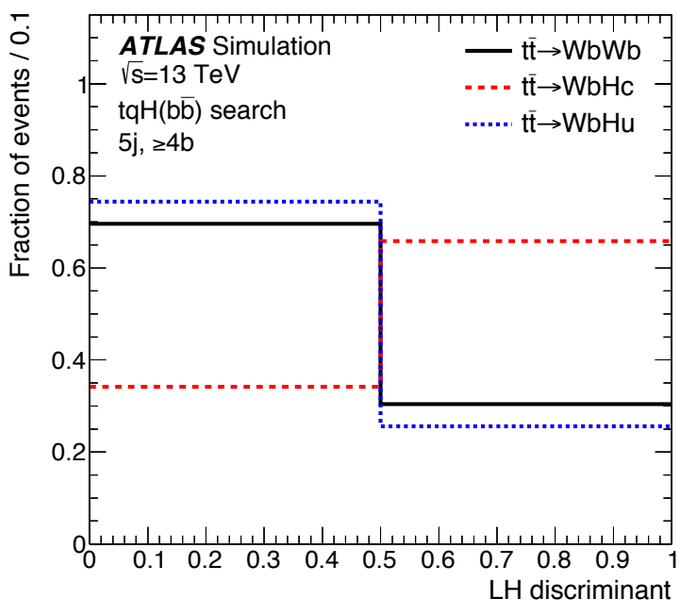










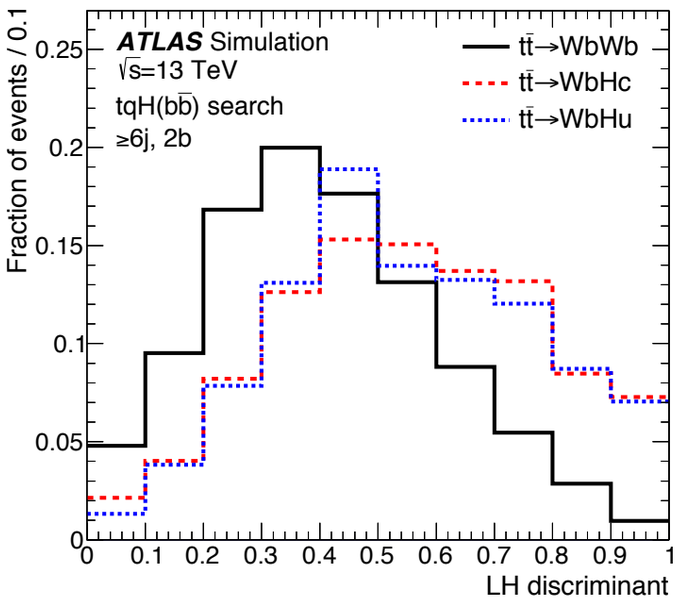


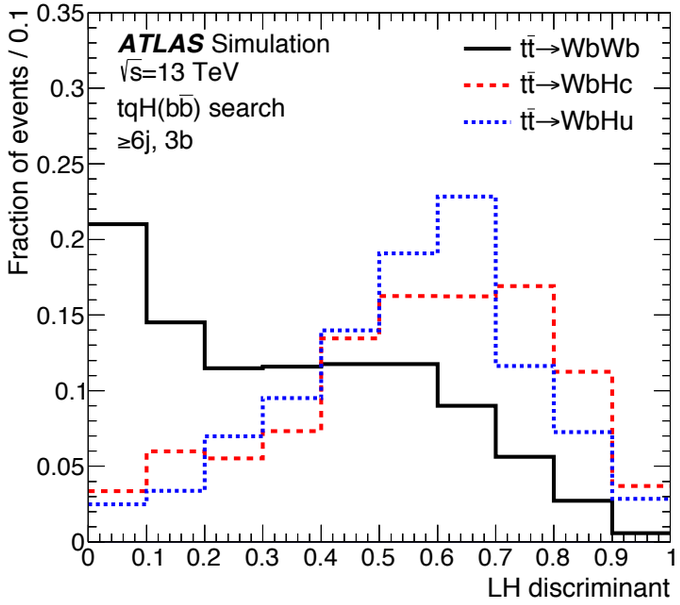
arXiv:1812.11568 submitted to JHEP

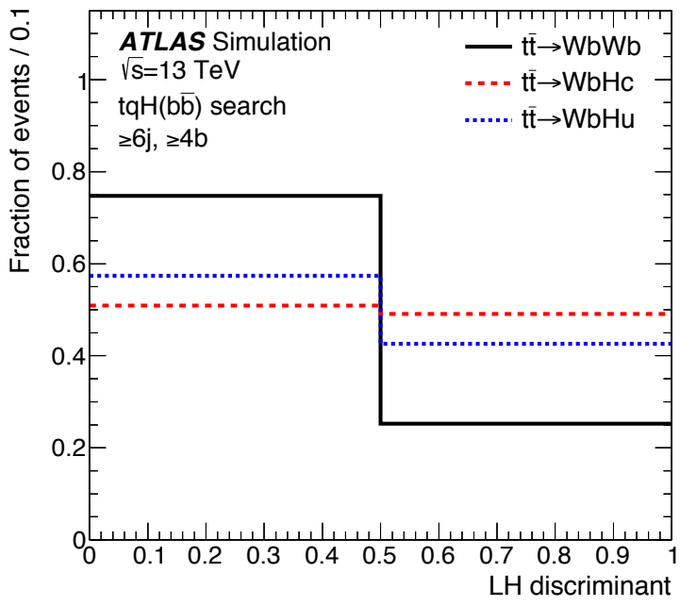
2015/16 Dataset
36.1 fb^{-1}

FCNC tHq ATLAS

H->bb likelihood discriminant shapes







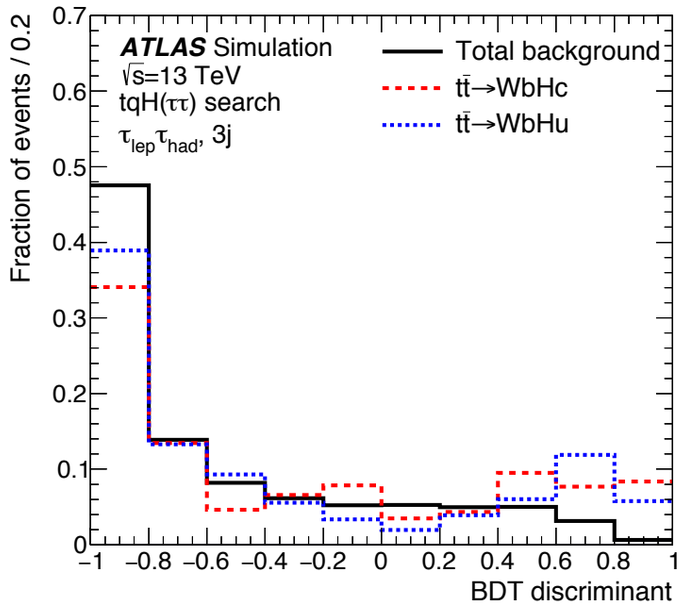
arXiv:1812.11568 submitted to JHEP

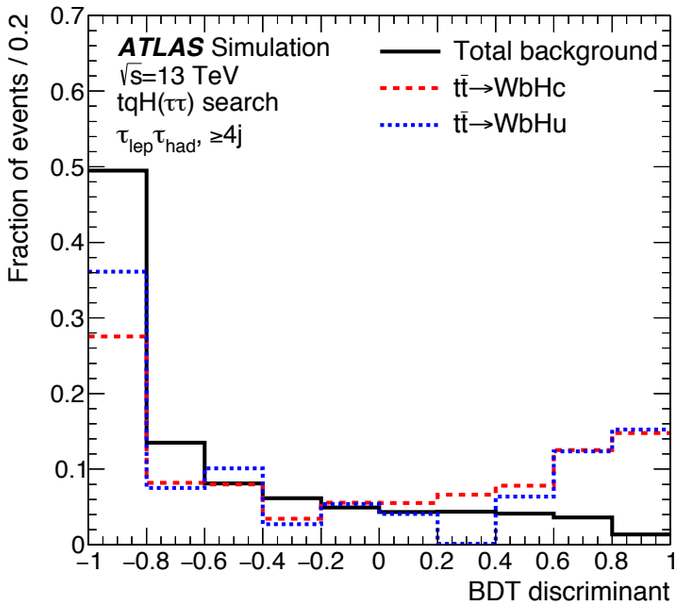
2015/16 Dataset
36.1 fb-1

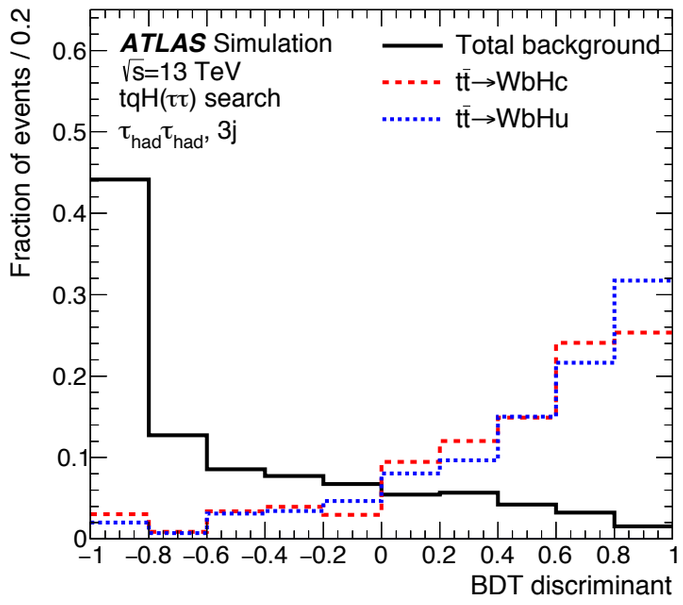
FCNC tHq ATLAS

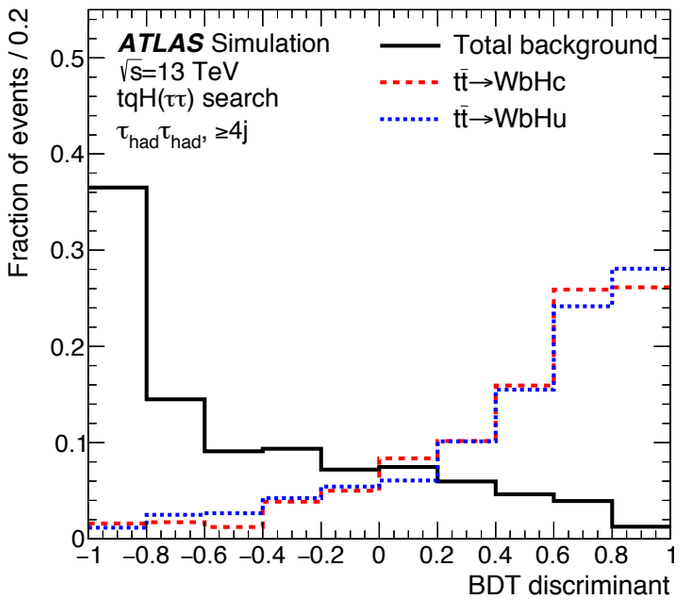
H->tau tau BDT shapes

Variable	$\tau_{\text{lep}}\tau_{\text{had}}$ 3j	$\tau_{\text{lep}}\tau_{\text{had}}$ ≥4j	$\tau_{\text{had}}\tau_{\text{had}}$ 3j	$\tau_{\text{had}}\tau_{\text{had}}$ ≥4j
$m_{\tau\tau}^{\text{fit}}$	×	×	×	×
m_{Hq}	×	×	×	×
$m_{\text{T,lep}}$	×	×		
$p_{\text{T},1}$	×	×	×	×
$p_{\text{T},2}$	×	×	×	×
$E_{\text{T}}^{\text{miss}}$ ϕ centrality	×	×	×	×
$E_{\text{T},\parallel}^{\text{miss}}$	×	×	×	×
$E_{\text{T},\perp}^{\text{miss}}$	×	×		
m_{bj_1}	×	×	×	×
$m_{\text{lep}j}$	×	×		
$m_{\tau j}$	×	×		
x_1^{fit}	×	×	×	×
x_2^{fit}	×	×	×	×
$m_{bj_1j_2}$		×		×







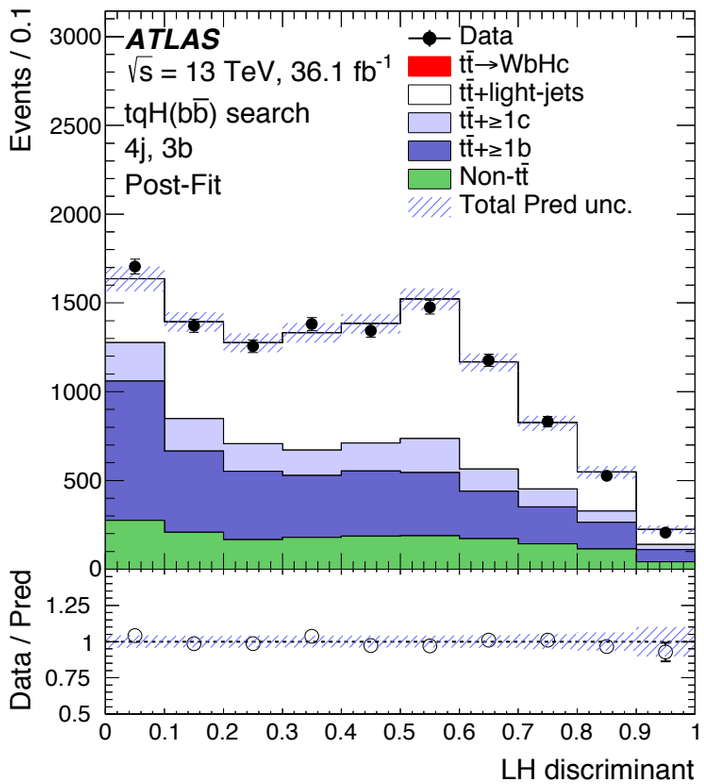


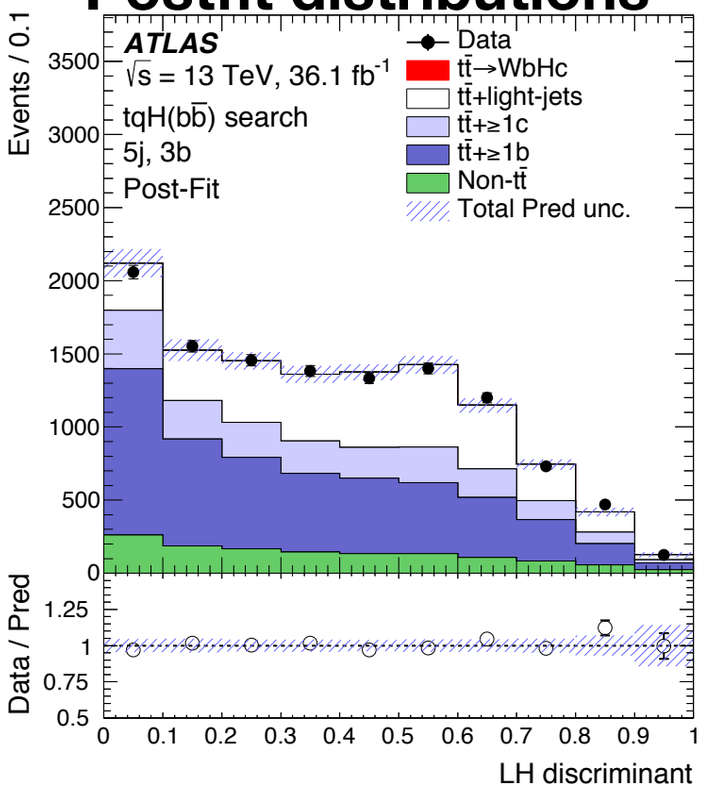
arXiv:1812.11568 submitted to JHEP

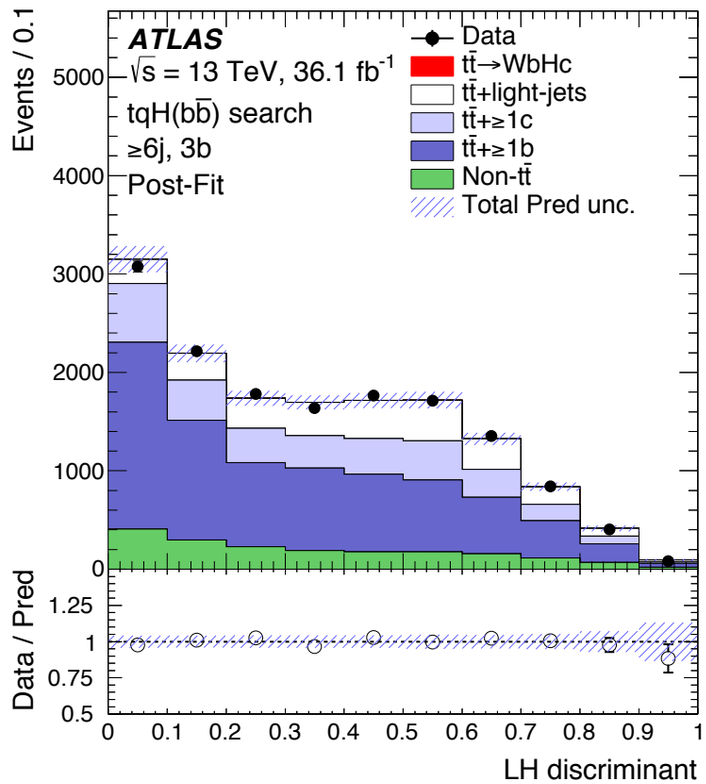
2015/16 Dataset
36.1 fb^{-1}

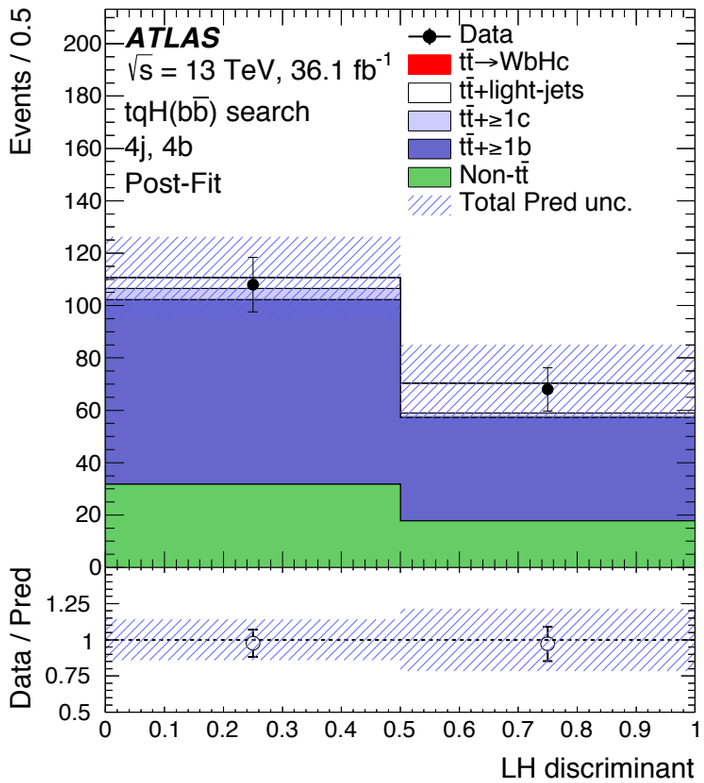
FCNC tHq ATLAS

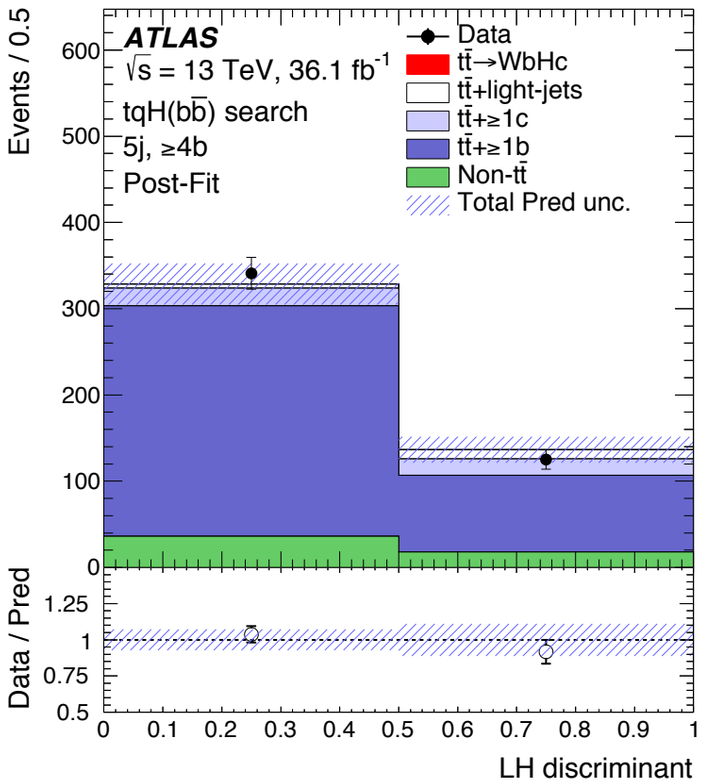
Postfit distributions

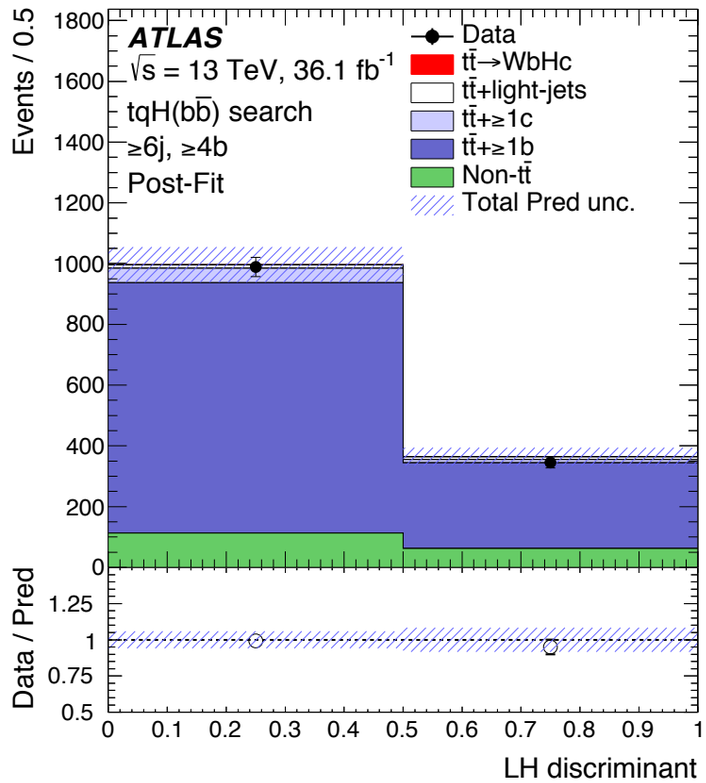










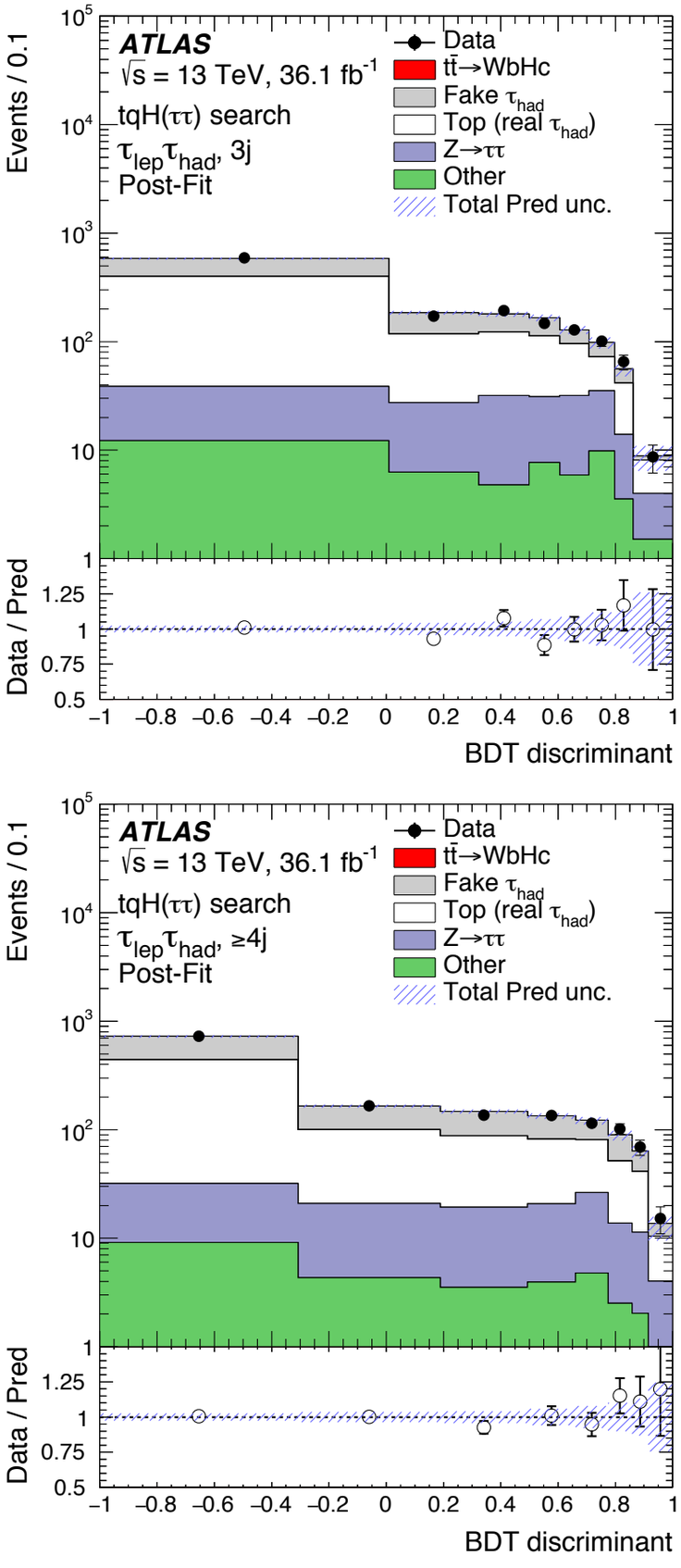


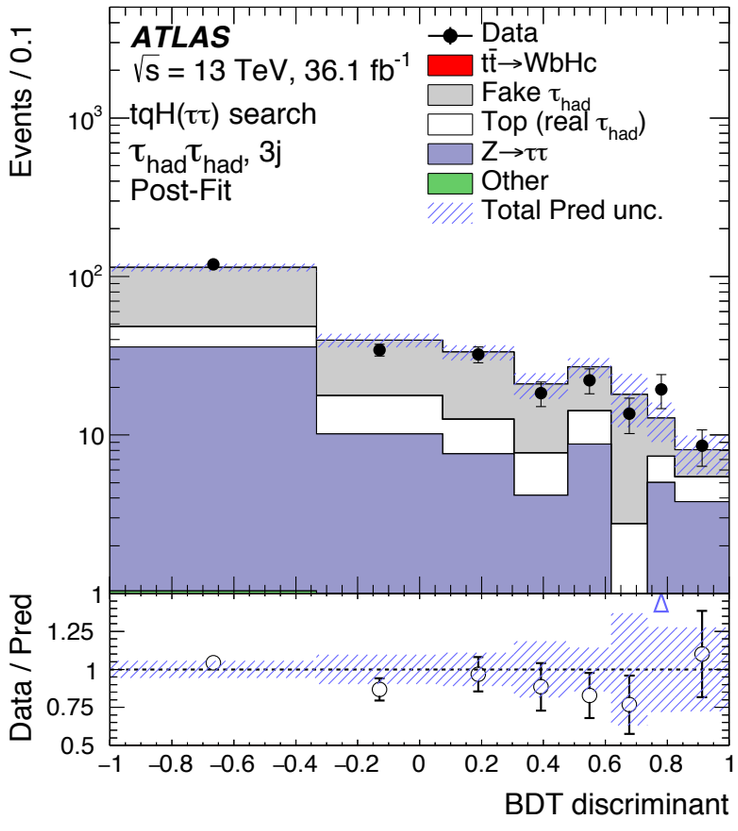
arXiv:1812.11568 submitted to JHEP

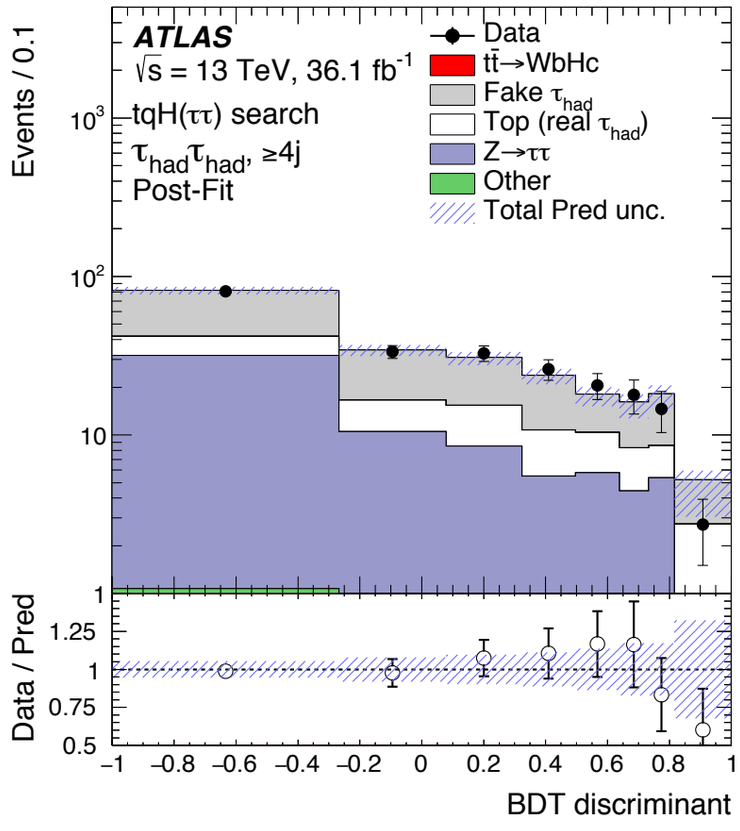
FCNC tHq ATLAS

Postfit distributions

2015/16 Dataset
36.1 fb^{-1}





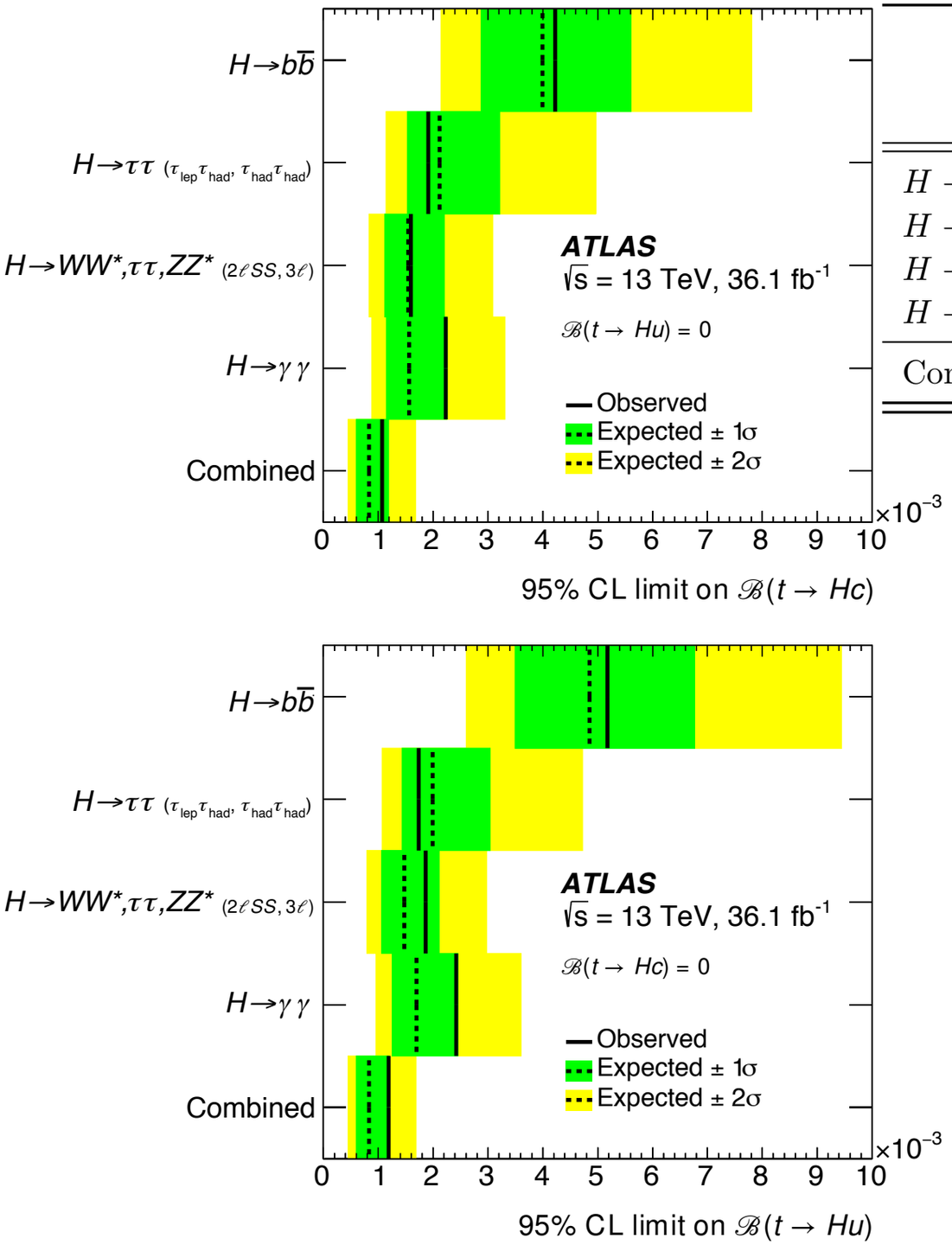


arXiv:1812.11568 submitted to JHEP

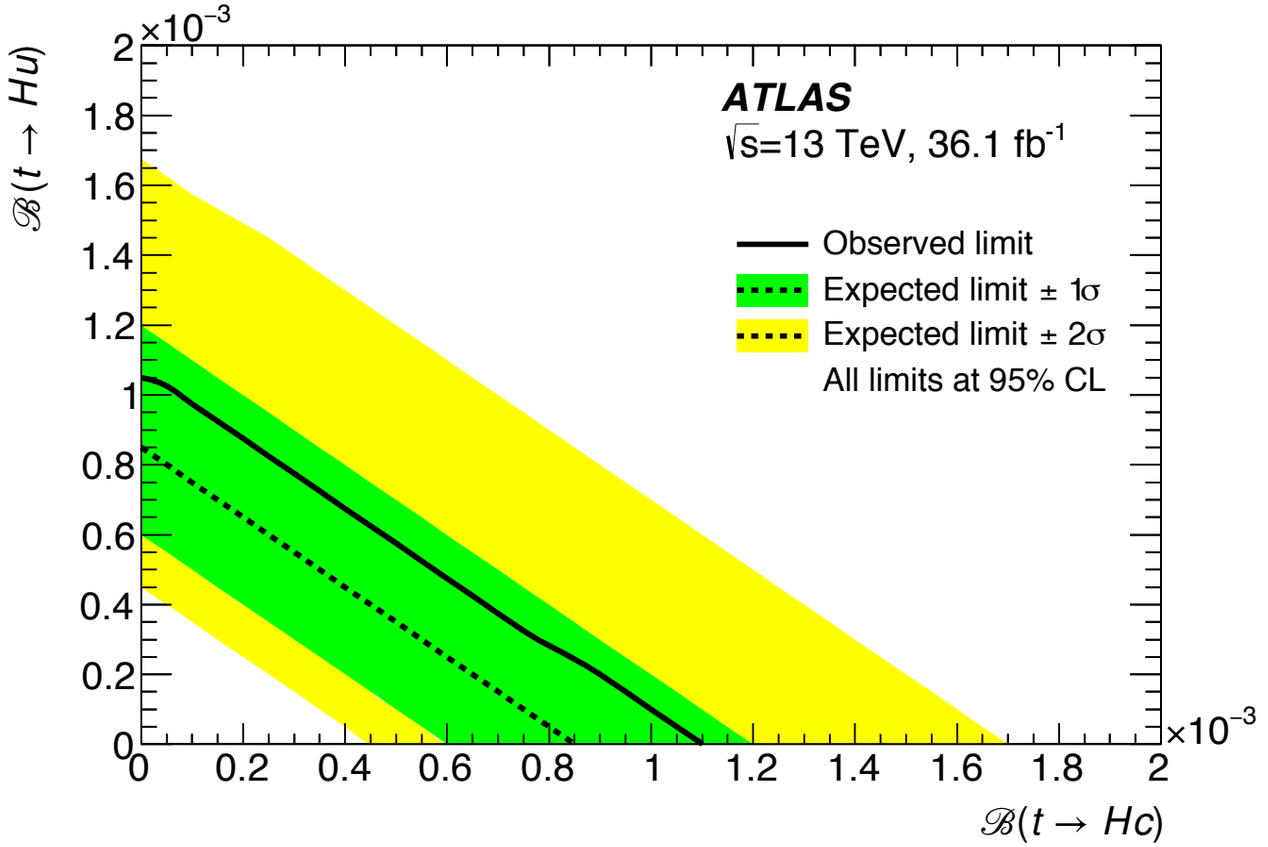
2015/16 Dataset
36.1 fb^{-1}

FCNC tHq ATLAS

Limits on t->Hq branching ratio



	95% CL upper limits on $B(t \to Hc)$ Observed (Expected)	95% CL upper limits on $B(t \to Hu)$ Observed (Expected)
$H \to b\bar{b}$	4.2×10^{-3} (4.0×10^{-3})	5.2×10^{-3} (4.9×10^{-3})
$H \to \tau\tau$ $(\tau_{\text{lep}}\tau_{\text{had}},\ \tau_{\text{had}}\tau_{\text{had}})$	1.9×10^{-3} (2.1×10^{-3})	1.7×10^{-3} (2.0×10^{-3})
$H \to WW^*, \tau\tau, ZZ^*$ $(2\ell\text{SS},\ 3\ell)$ [22]	1.6×10^{-3} (1.5×10^{-3})	1.9×10^{-3} (1.5×10^{-3})
$H \to \gamma\gamma$ [21]	2.2×10^{-3} (1.6×10^{-3})	2.4×10^{-3} (1.7×10^{-3})
Combination	1.1×10^{-3} (8.3×10^{-4})	1.2×10^{-3} (8.3×10^{-4})

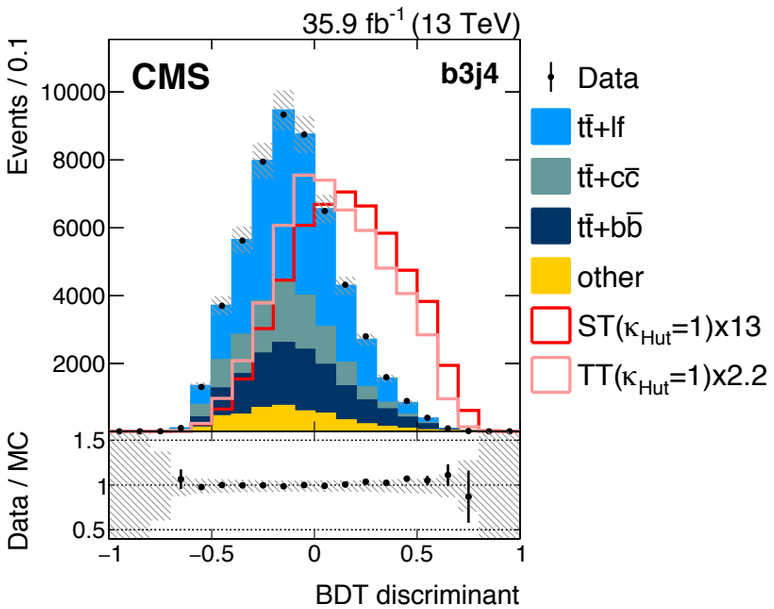


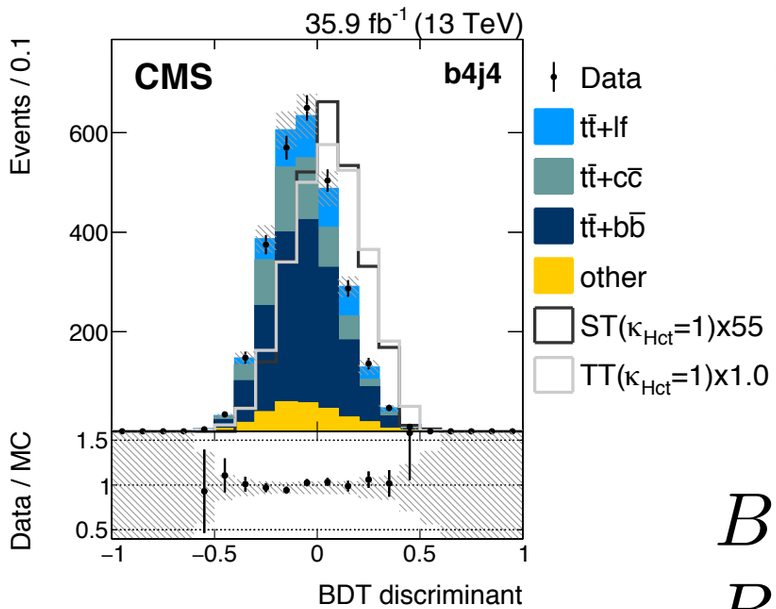
arXiv:1812.11568 submitted to JHEP

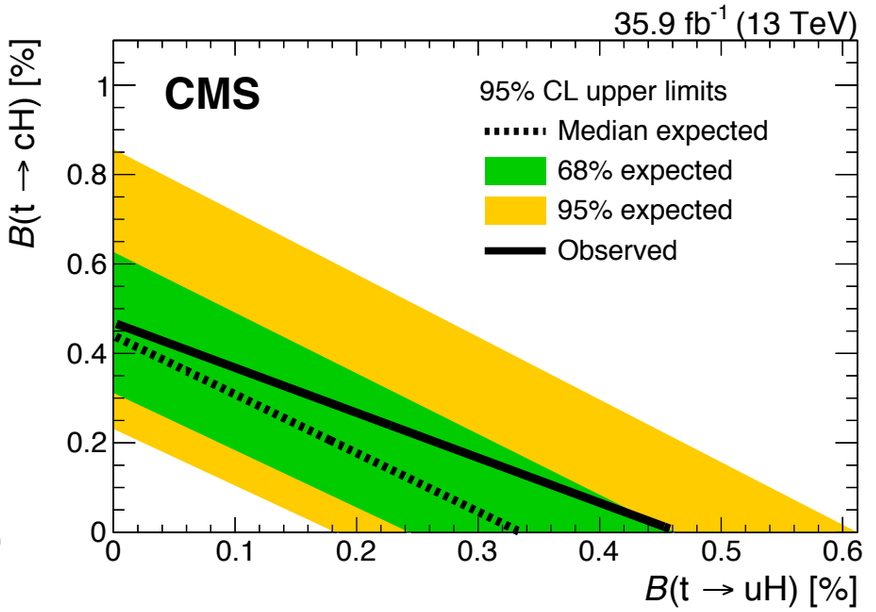
2016 Dataset
35.9 fb^{-1}

FCNC tHq CMS

- Search for tHq FCNC in decays of top quark pairs or production of single top
- Measuring H->bb decays
  - Final state of isolated lepton, ≥3 jets, ≥2 b-jets
- 5 signal regions, defined based on jet/b-jet multiplicities
  - Exactly 3 jets, with 2 or 3 b-jets: b2j3, b3j3,
  - At least 4 jets, with 2, 3, or 4 b-jets: b2j4, b3j4, b4j4
- BDT to discriminate signal from backgrounds





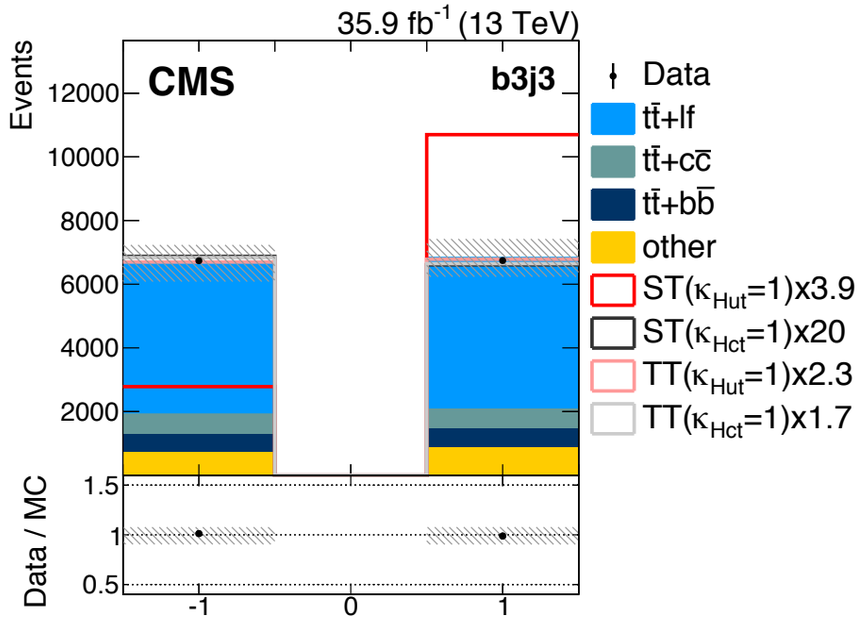


$$B(t \to uH) < 0.47\%(0.34\%)$$
$$B(t \to cH) < 0.47\%(0.44\%)$$

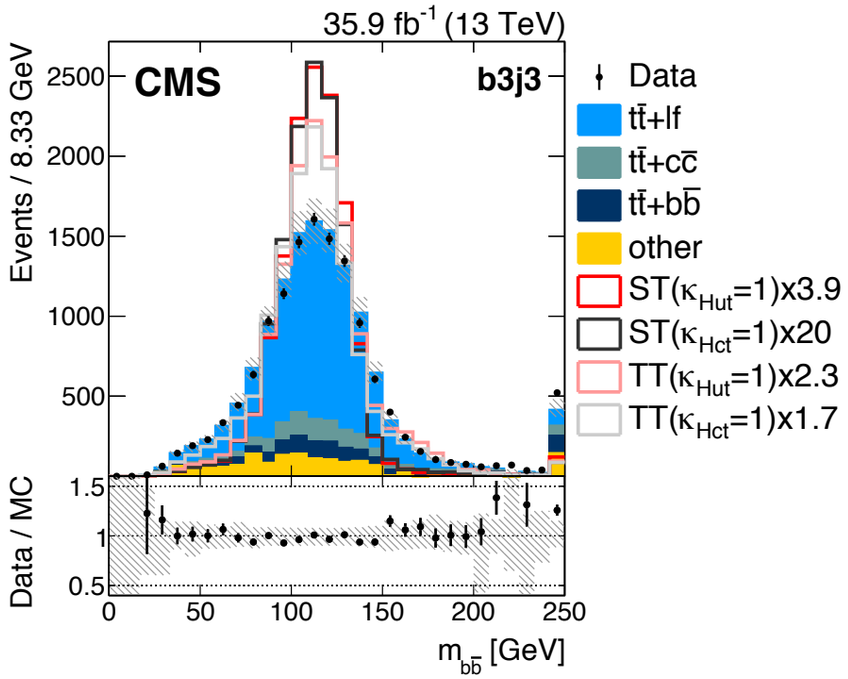
JHEP 06 (2018) 102 (arXiv:1712.02399)

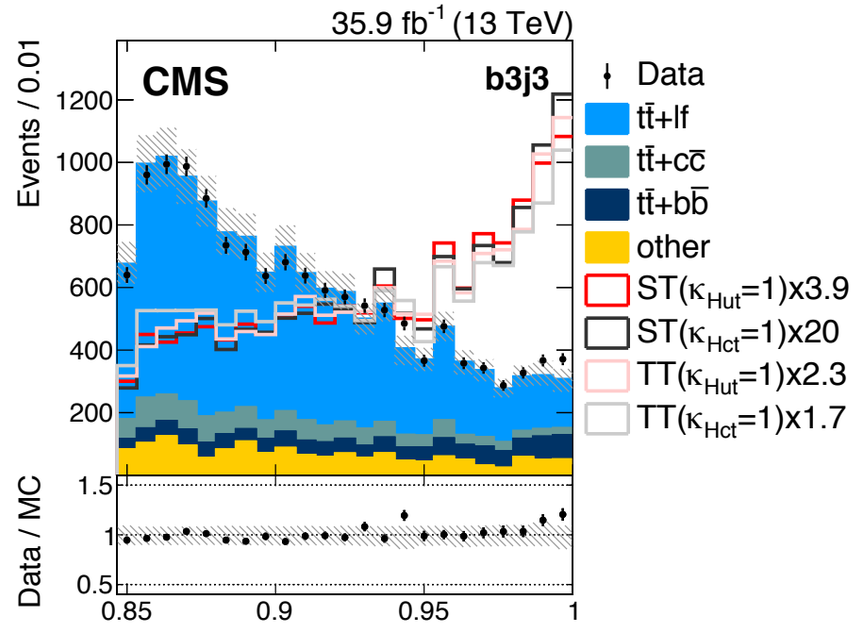
2016 Dataset
35.9 fb^{-1}

FCNC tHq CMS

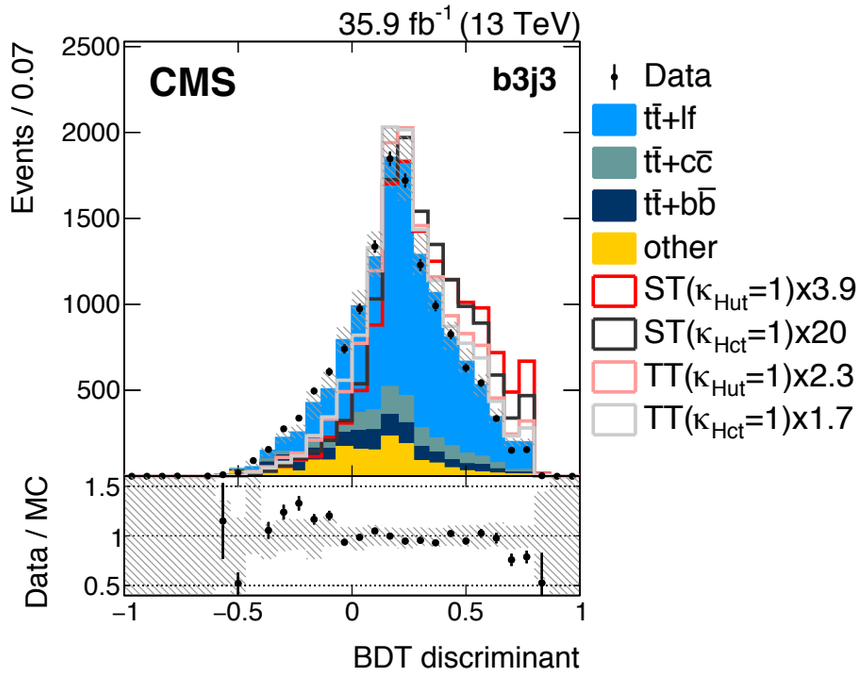


Lepton charge





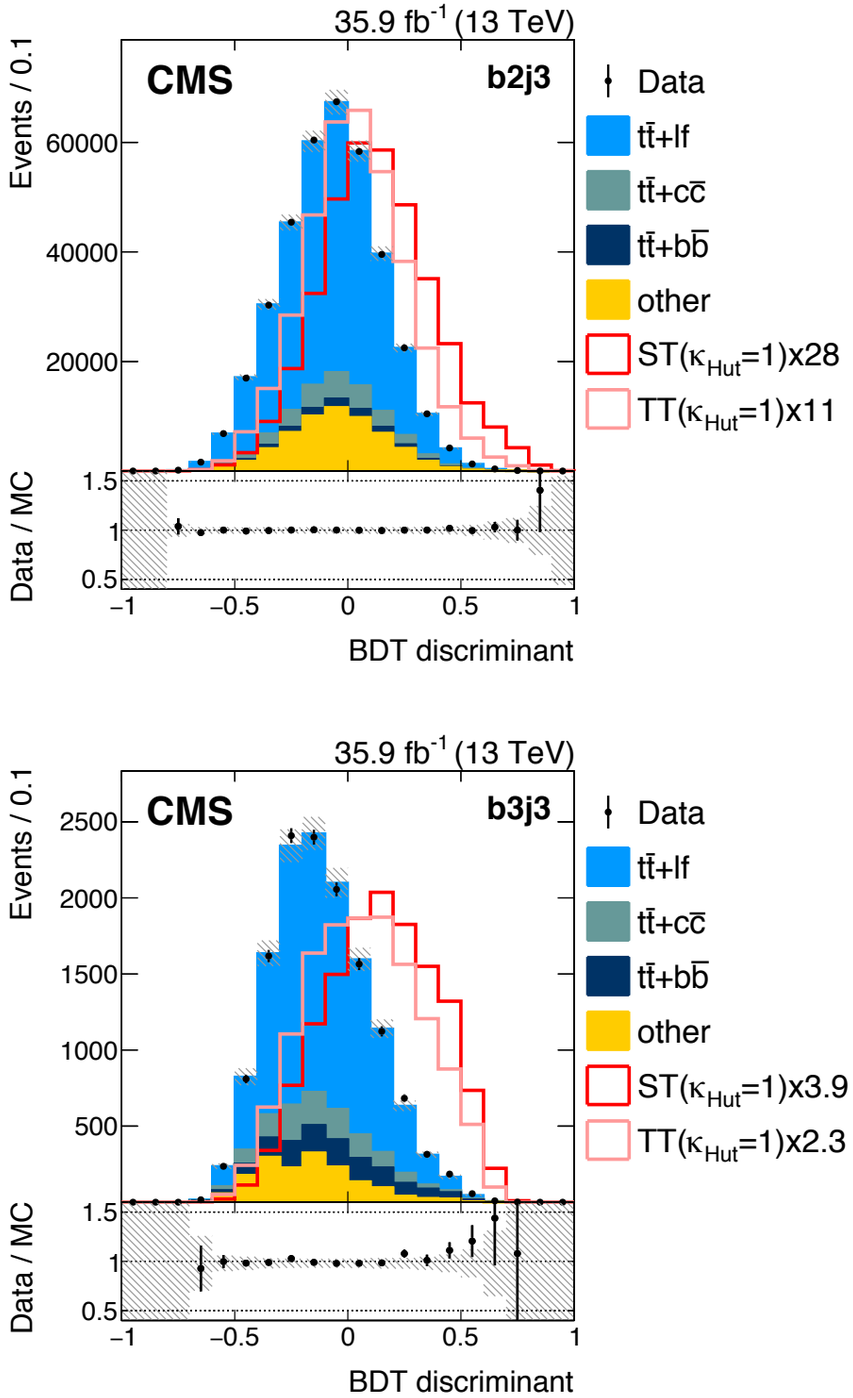
b jet CSVv2 discriminant

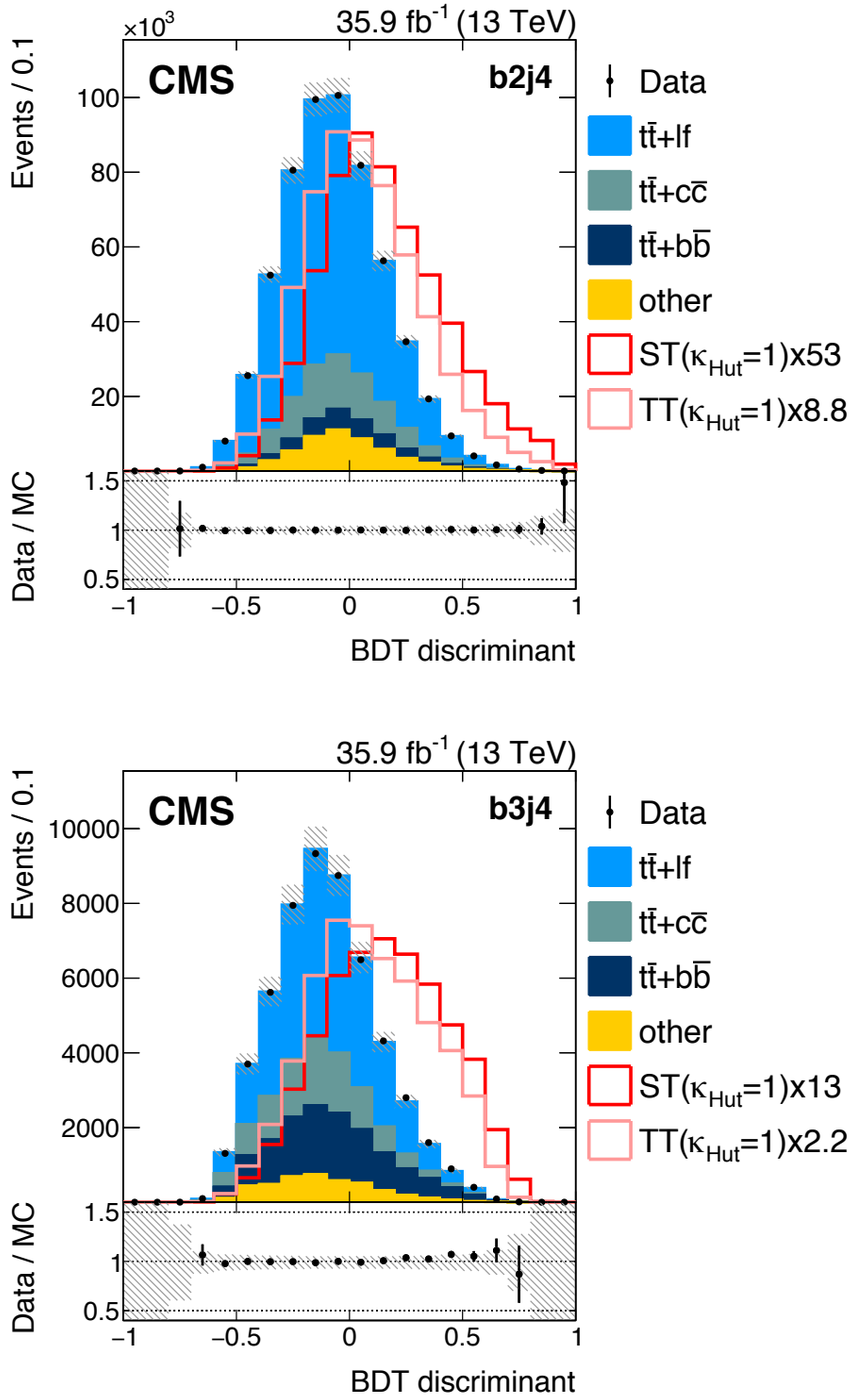


JHEP 06 (2018) 102 (arXiv:1712.02399)

2016 Dataset
35.9 fb^{-1}

FCNC tHq CMS

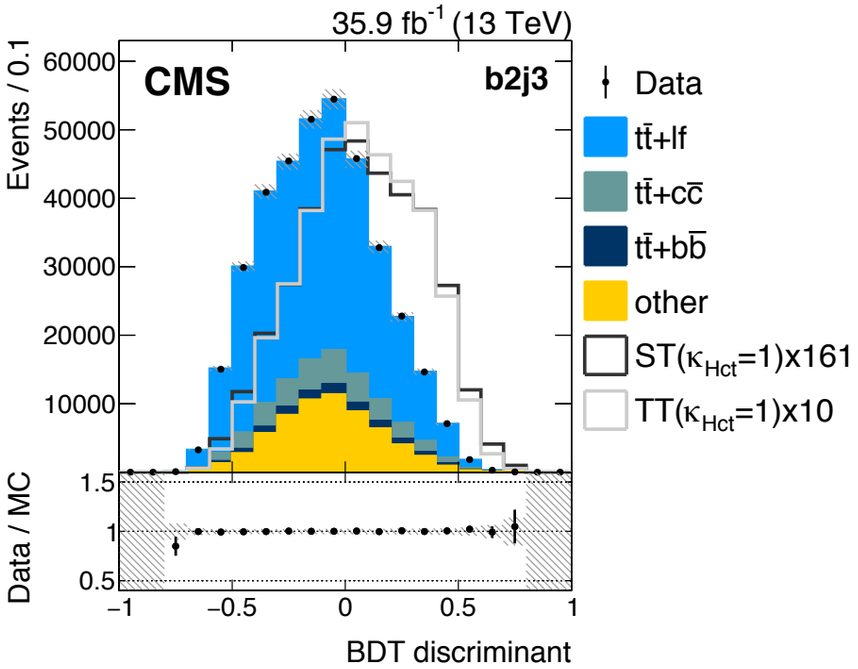


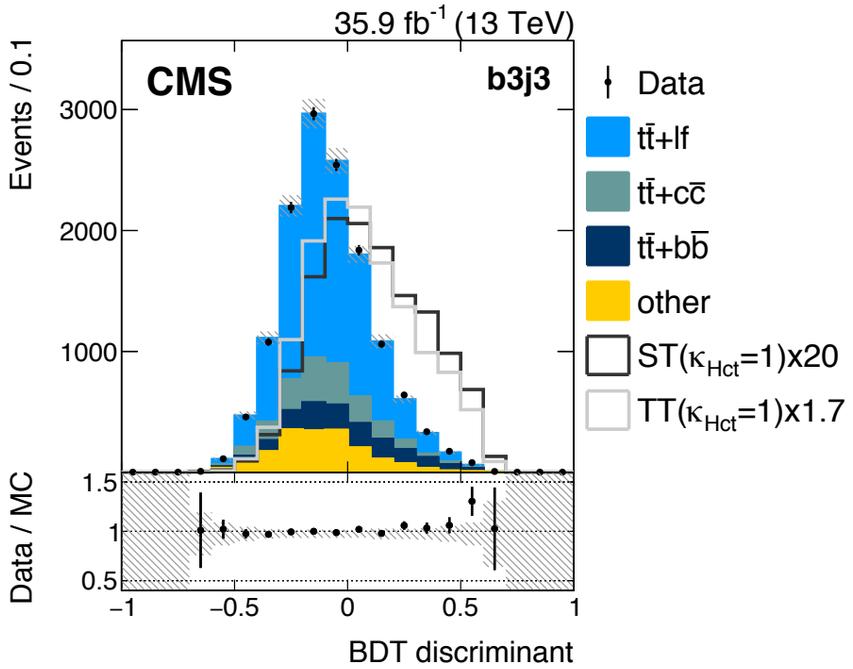


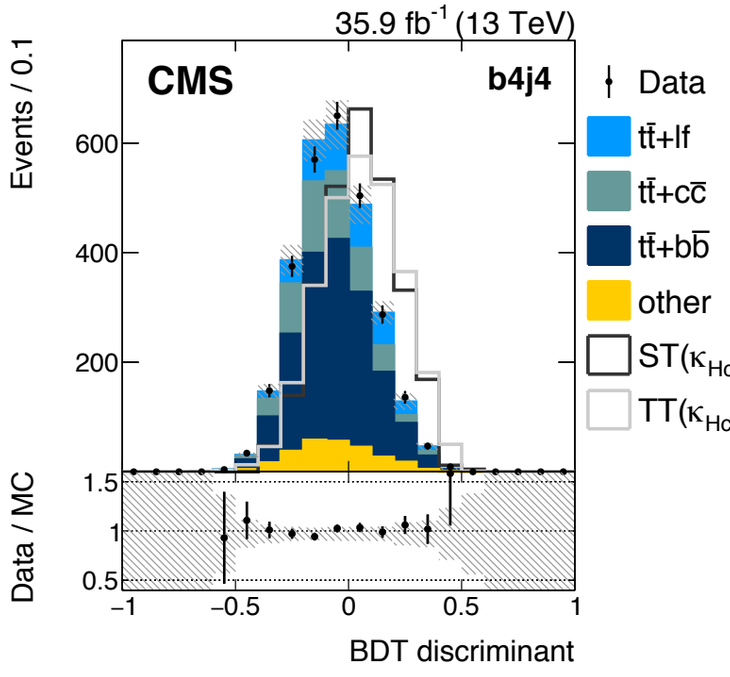
JHEP 06 (2018) 102 (arXiv:1712.02399)

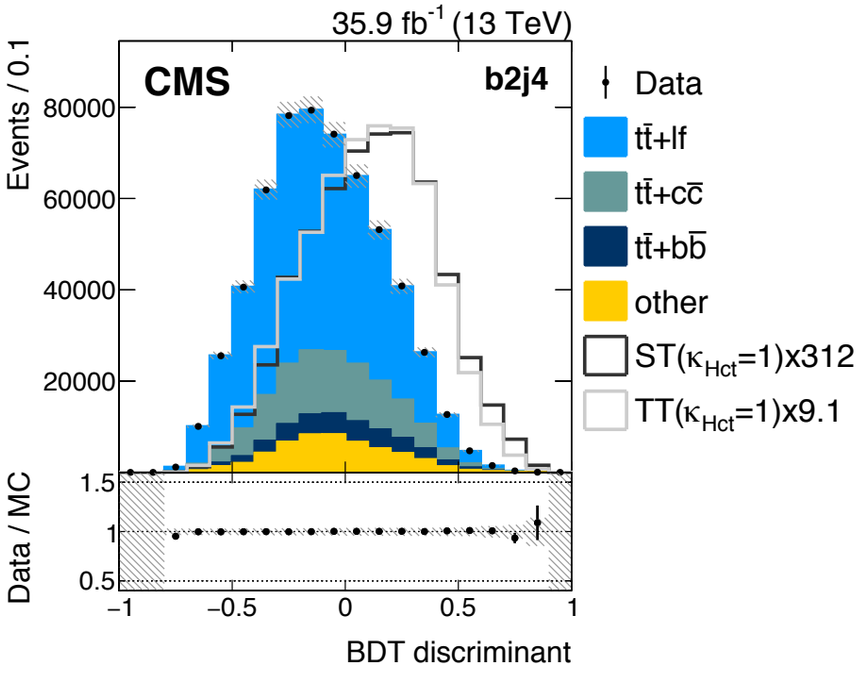
2016 Dataset
35.9 fb^{-1}

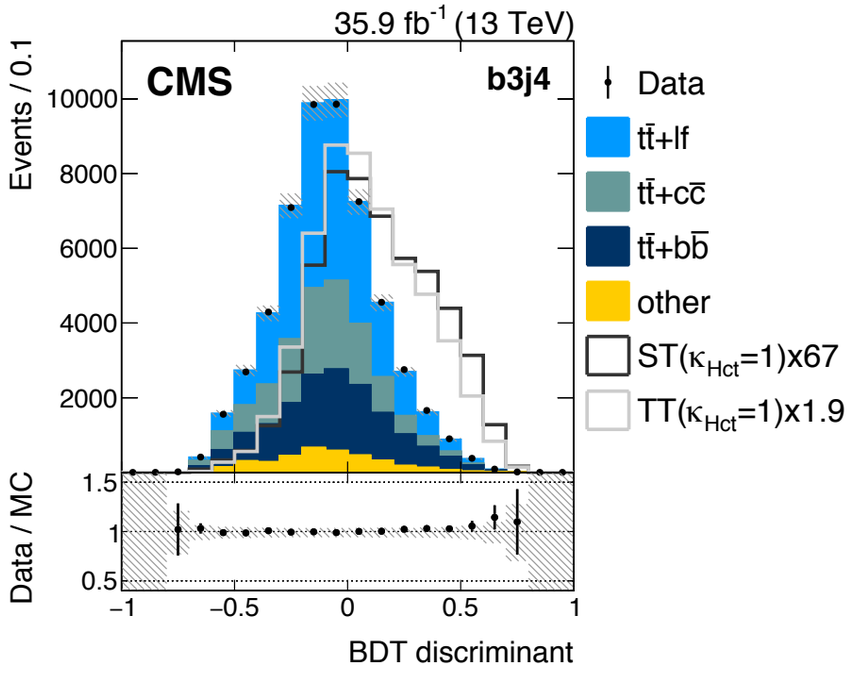
FCNC tHq CMS









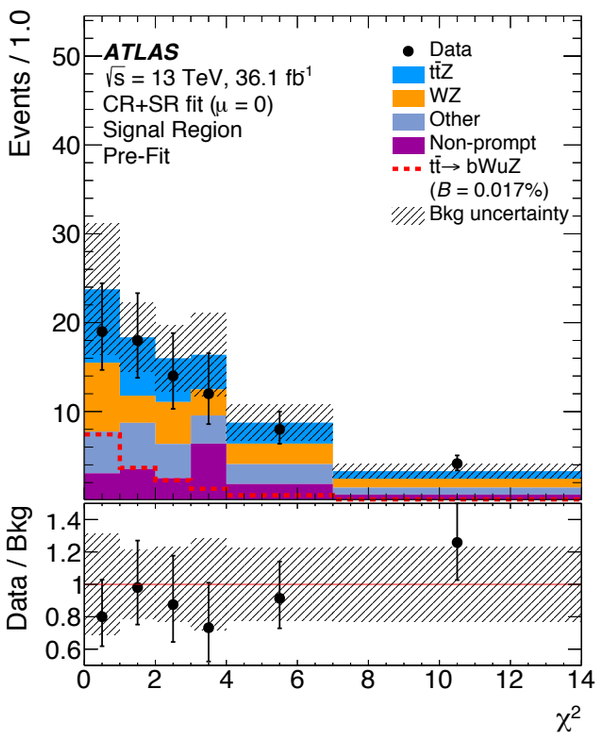


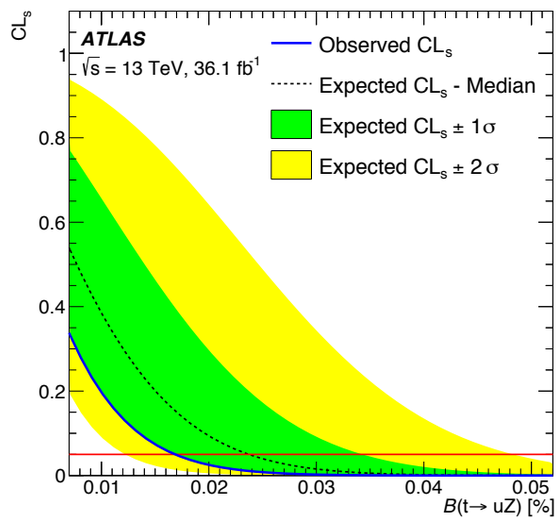
JHEP 06 (2018) 102 (arXiv:1712.02399)

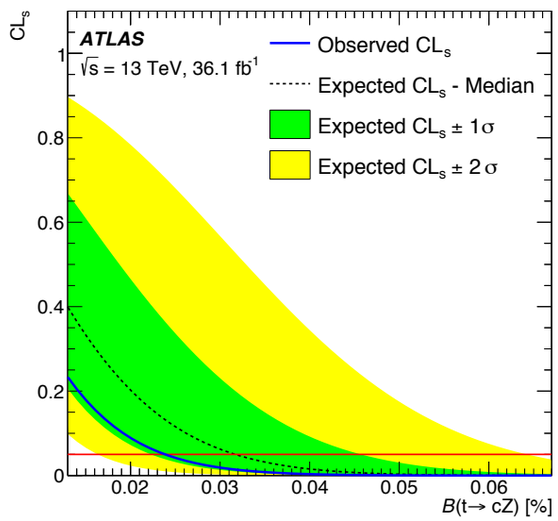
2015/16 Dataset
36.1 fb^{-1}

FCNC tZq ATLAS

- Search in top pair production, with one top decaying to a Z boson and up-type quark
  - Measured in 3 lepton final state, containing OS SF pair consistent with Z mass, ≥2 jets, =1 b-tagged
  - Reconstruct FCNC top pair with χ^2-fit $\chi^2 = \frac{\left(m^{\text{reco}}_{j_a\ell_a\ell_b} - m_{t_{\text{FCNC}}}\right)^2}{\sigma^2_{t_{\text{FCNC}}}} + \frac{\left(m^{\text{reco}}_{j_b\ell_c\nu} - m_{t_{\text{SM}}}\right)^2}{\sigma^2_{t_{\text{SM}}}} + \frac{\left(m^{\text{reco}}_{\ell_c\nu} - m_W\right)^2}{\sigma^2_W},$
- Signal region where reconstructed tops within 40 GeV of top mass, W boson within 30 GeV of W mass
- Control regions defined for ttZ, WZ, ZZ, and non-prompt backgrounds
- Varying lepton / jet / b-tag multiplicities







$$B(t \to uZ) < 1.7 \times 10^{-4} (2.4 \times 10^{-4})$$
$$B(t \to cZ) < 2.4 \times 10^{-4} (3.2 \times 10^{-4})$$

JHEP 07 (2018) 176 (arXiv:1803.09923)

2015/16 Dataset
36.1 fb-1

FCNC tZq ATLAS

ATLAS EXPERIMENT

Selection	$t\bar{t}Z$ CR	WZ CR	ZZ CR	Non-prompt lepton CR0 (CR1)	SR
No. leptons	3	3	4	3	3
OSSF	Yes	Yes	Yes	Yes	Yes
$\lvert m_{\ell\ell}^{\text{reco}} - 91.2\ \text{GeV}\rvert$	< 15 GeV	< 15 GeV	< 15 GeV	> 15 GeV	< 15 GeV
No. jets	≥ 4	≥ 2	≥ 1	≥ 2	≥ 2
No. b-tagged jets	2	0	0	0 (1)	1
$E_{\text{T}}^{\text{miss}}$	> 20 GeV	> 40 GeV	> 20 GeV	> 20 GeV	> 20 GeV
$m_{\text{T}}^{\ell\nu}$	-	> 50 GeV	-	-	-
$\lvert m_{\ell\nu}^{\text{reco}} - 80.4\ \text{GeV}\rvert$	-	-	-	-	< 30 GeV
$\lvert m_{j\ell\nu}^{\text{reco}} - 172.5\ \text{GeV}\rvert$	-	-	-	-	< 40 GeV
$\lvert m_{j\ell\ell}^{\text{reco}} - 172.5\ \text{GeV}\rvert$	-	-	-	-	< 40 GeV

Sample	$t\bar{t}Z$ CR	WZ CR	ZZ CR	Non-prompt lepton CR0	Non-prompt lepton CR1
$t\bar{t}Z$	61 ± 9	16.3 ± 3.1	0 ± 0	6.1 ± 1.2	22.1 ± 3.2
WZ	9 ± 9	560 ± 240	0 ± 0	150 ± 70	20 ± 9
ZZ	0.07 ± 0.03	48 ± 11	92 ± 20	58 ± 16	9.0 ± 2.3
Non-prompt leptons	3 ± 6	28 ± 16	0 ± 0	150 ± 50	140 ± 70
Other backgrounds	13.4 ± 2.7	22 ± 5	1.0 ± 0.6	17 ± 6	32 ± 6
Total background	87 ± 15	670 ± 240	93 ± 20	380 ± 90	230 ± 70
Data	81	734	87	433	260
Data / Bkg	0.94 ± 0.19	1.1 ± 0.4	0.94 ± 0.23	1.13 ± 0.28	1.1 ± 0.4

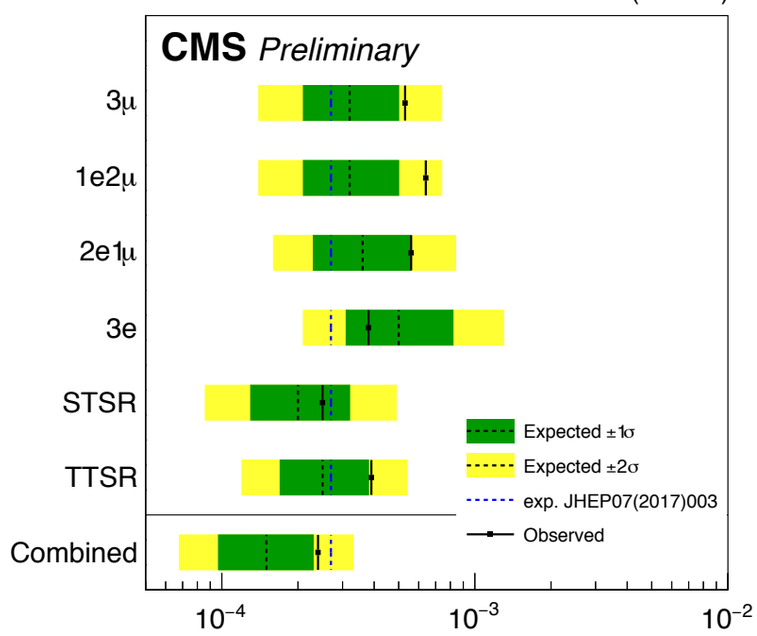
JHEP 07 (2018) 176 (arXiv:1803.09923)

2016 Dataset
35.9 fb^{-1}

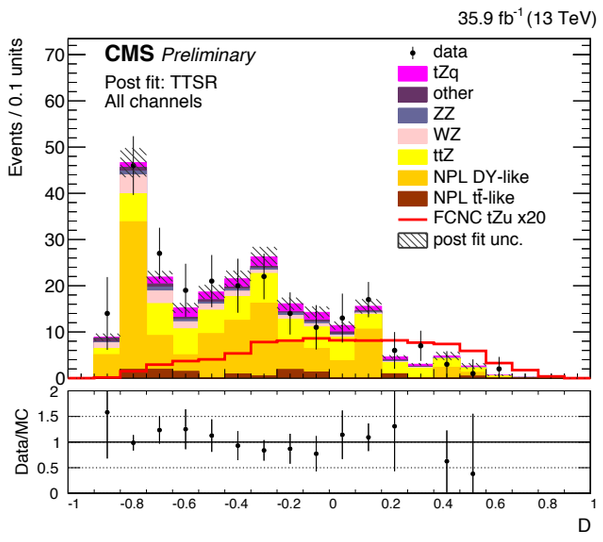
FCNC tZq CMS

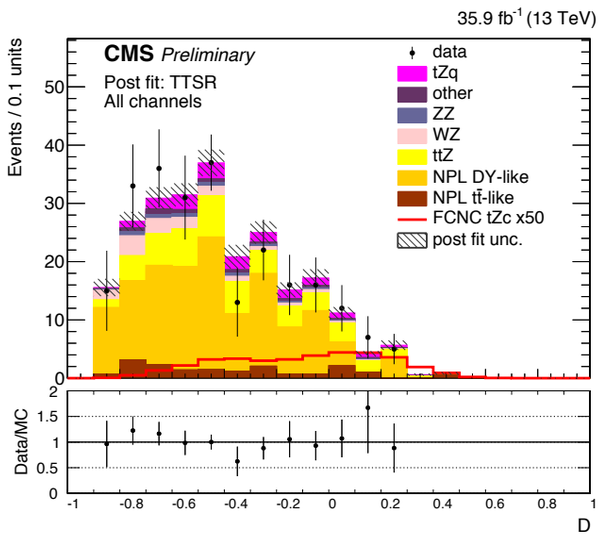
- Search for tZq FCNC in decays of top quark pairs or production of single top
- Measurement in the 3 lepton final state (3e, 2e1μ, 1e2μ, 3μ)

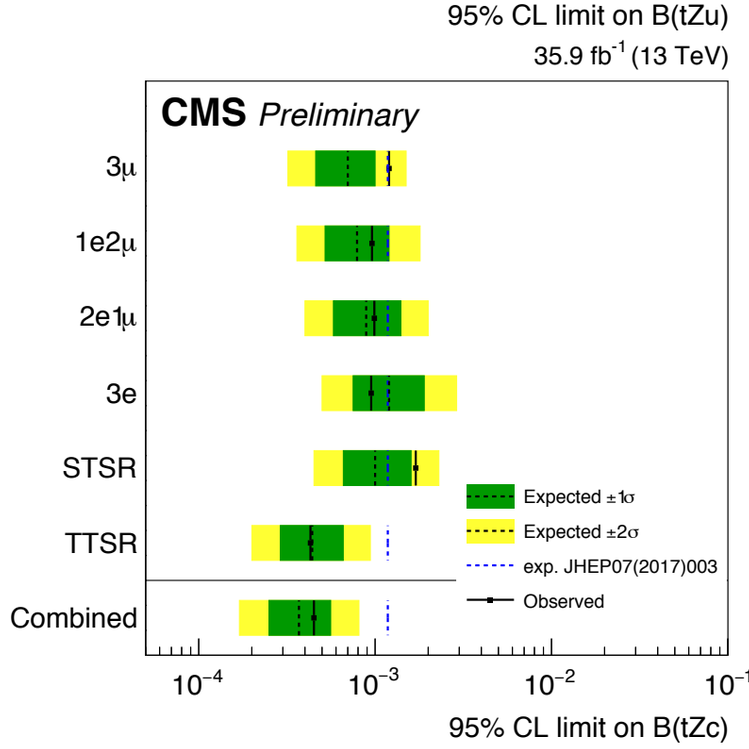
	WZ control region (WZCR)	single top quark signal region (STSR)	top quark pair signal region (TTSR)	single top quark control region (STCR)	top quark pair control region (TTCR)
Number of jets	$\geq 1, \leq 3$	1	$\geq 2, \leq 3$	1	$\geq 2, \leq 3$
Number of b jets	0	1	≥ 1	1	≥ 1
$\lvert M(Z_{\text{reco}}) - M_Z \rvert < 7.5$ GeV	Yes	Yes	Yes	No	No



- BDT trained in tt and single top signal regions
  - Using separation between objects, masses, and b-tagging information







$$B(t \to uZ) < 0.024\%(0.015\%)$$
$$B(t \to cZ) < 0.045\%(0.037\%)$$

CMS PAS TOP-17-017

2016 Dataset
35.9 fb^{-1}

New Physics via top production

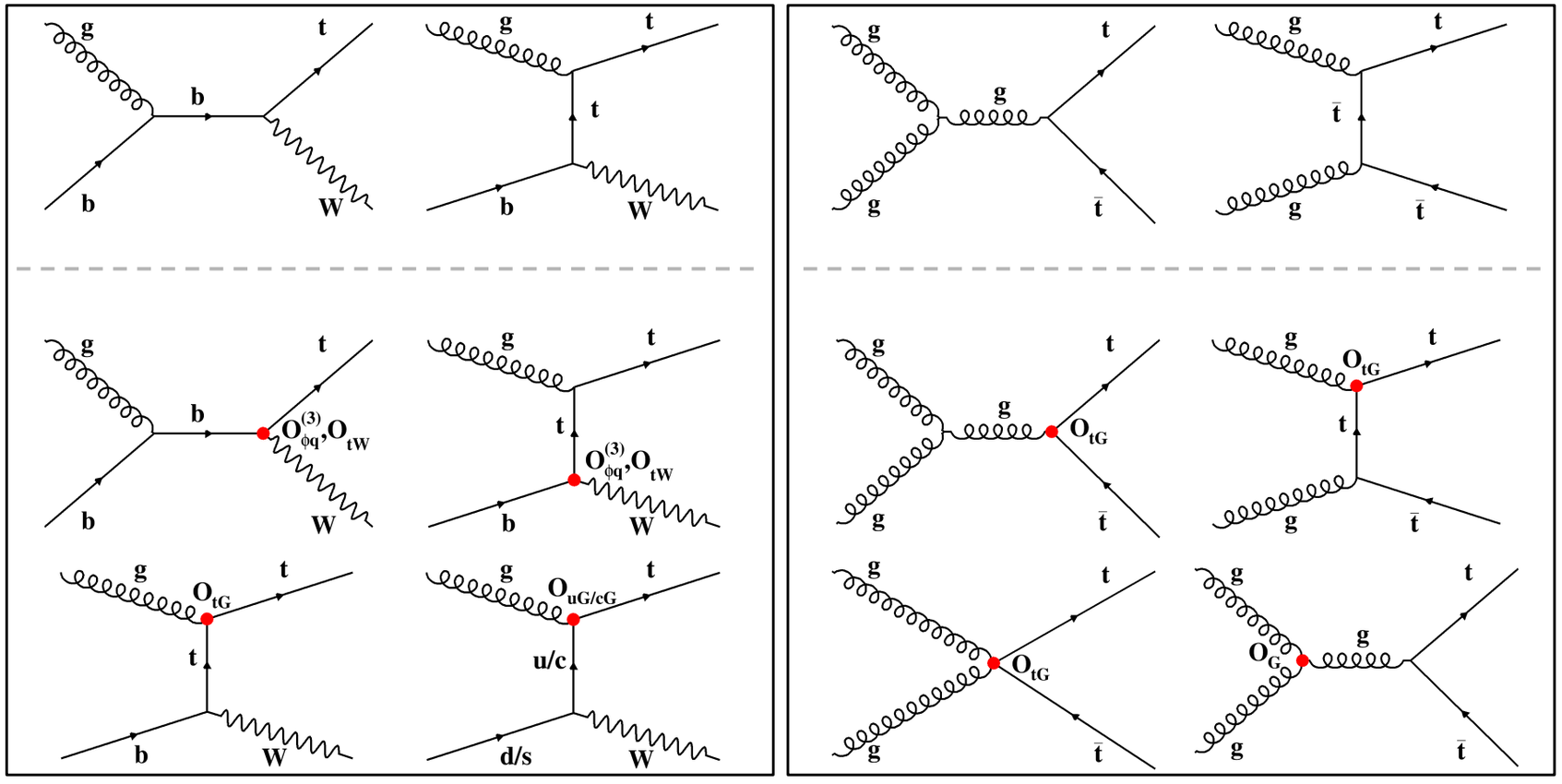
$$O_{\phi q}^{(3)} = (\phi^+ \tau^I D_\mu \phi)(\bar{q}\gamma^\mu \tau^I q), \quad L_{eff} = \frac{C_{\phi q}^{(3)}}{\sqrt{2}\Lambda^2} g v^2 \bar{b}\gamma^\mu P_L t W_\mu^- + h.c.,$$

$$O_{tW} = (\bar{q}\sigma^{\mu\nu}\tau^I t)\tilde{\phi} W_{\mu\nu}^I, \quad L_{eff} = -2\frac{C_{tW}}{\Lambda^2} v \bar{b}\sigma^{\mu\nu} P_R t \partial_\nu W_\mu^- + h.c.,$$

$$O_{tG} = (\bar{q}\sigma^{\mu\nu}\lambda^A t)\tilde{\phi} G_{\mu\nu}^A, \quad L_{eff} = \frac{C_{tG}}{\sqrt{2}\Lambda^2} v \left(\bar{t}\sigma^{\mu\nu}\lambda^A t\right) G_{\mu\nu}^A + h.c.,$$

$$O_G = f_{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}, \quad L_{eff} = \frac{C_G}{\Lambda^2} f_{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu} + h.c.,$$

$$O_{u(c)G} = (\bar{q}\sigma^{\mu\nu}\lambda^A t)\tilde{\phi} G_{\mu\nu}^A, \quad L_{eff} = \frac{C_{u(c)G}}{\sqrt{2}\Lambda^2} v \left(\bar{u}\,(\bar{c})\,\sigma^{\mu\nu}\lambda^A t\right) G_{\mu\nu}^A + h.c.,$$



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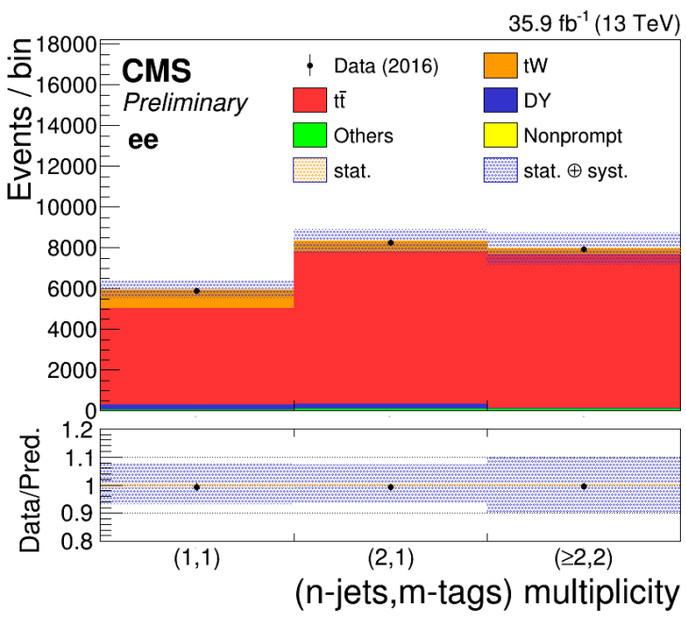
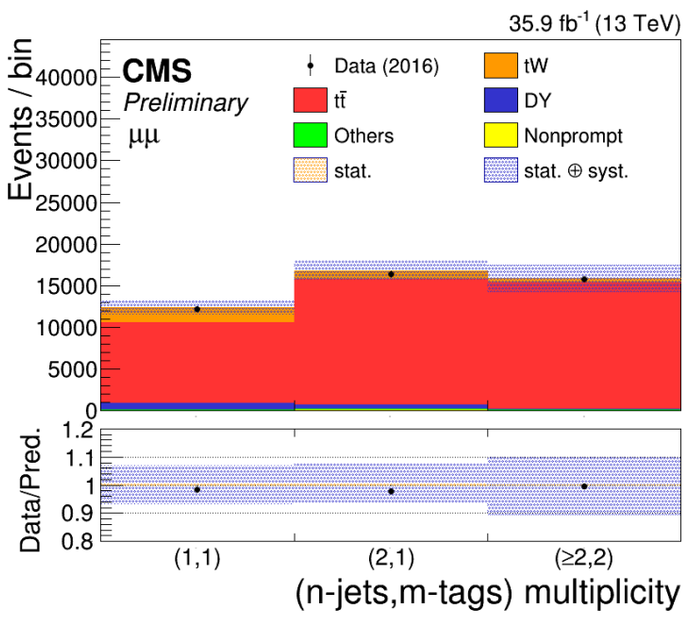
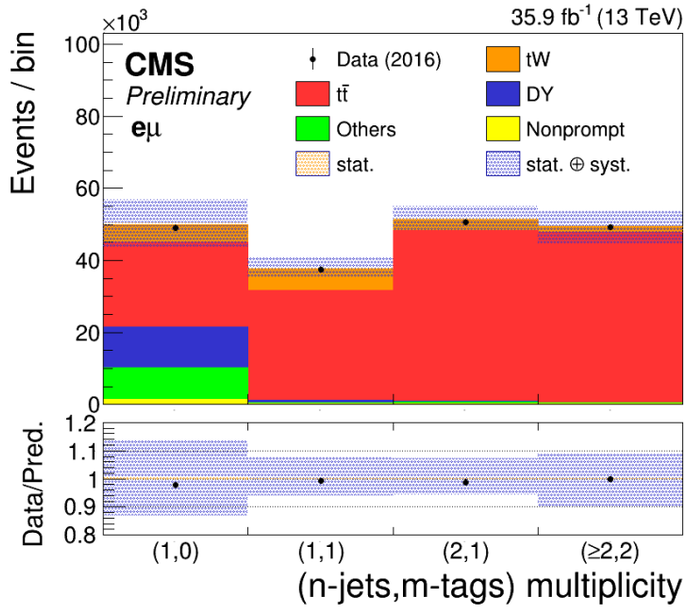
New Physics via top production

Event Yields in jet/b-jet multiplicity regions







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Neural net input variables

Variable	Description	NN_{10}	NN_{11}	NN_{21}	NN_{FCNC}
M_{ll}	Invariant mass of dilepton system	√			√
$p_T^{\ell\ell}$	p_T of dilepton system	√		√	√
$\Delta p_T(\ell,\ell)$	$p_T^{\text{leading lepton}}$ - $p_T^{\text{sub-leading lepton}}$	√			√
$p_T^{\text{leading lepton}}$	p_T of leading lepton	√		√	√
Centrality(ℓ^{leading},jet$^{\text{leading}}$)	Scalar sum of p_T of the leading lepton and leading jet, over total energy of selected objects	√			√
Centrality(ℓ,ℓ)	Scalar sum of p_T of the leading and sub-leading leptons, over total energy of selected objects	√			√
$\Delta\phi(\ell\ell$,jet$^{\text{leading}})$	$\Delta\phi$ between dilepton system and leading jet	√	√	√	
$p_T(\ell\ell$,jet$^{\text{leading}})$	p_T of dilepton and leading jet system		√		√
$p_T(\ell^{\text{leading}}$,jet$^{\text{leading}})$	p_T of leading lepton and leading jet system		√		
Centrality($\ell\ell$,jet$^{\text{leading}}$)	Scalar sum of p_T of the dilepton system and leading jet, over total energy of selected objects		√		
$\Delta R(\ell,\ell)$	ΔR between leading and sub-leading leptons		√		
$\Delta R(\ell^{\text{leading}}$,jet$^{\text{leading}})$	ΔR between leading lepton and leading jet		√		
$M(\ell^{\text{leading}}$,jet$^{\text{leading}})$	Invariant mass of leading lepton and leading jet			√	
M(jet$^{\text{leading}}$,jet$^{\text{sub-leading}}$)	Invariant mass of leading jet and sub-leading jet			√	
$\Delta R(\ell^{\text{leading}}$,jet$^{\text{sub-leading}})$	ΔR between leading lepton and sub-leading jet			√	
$\Delta R(\ell\ell$,jet$^{\text{leading}})$	ΔR between dilepton system and leading jet			√	√
$\Delta p_T(\ell^{\text{sub-leading}}$, jet$^{\text{sub-leading}})$	$p_T^{\text{sub-leading lepton}}$ - $p_T^{\text{sub-leading jet}}$			√	
$M(\ell^{\text{sub-leading}}$, jet$^{\text{leading}})$	Invariant mass of sub-leading lepton and leading jet				√

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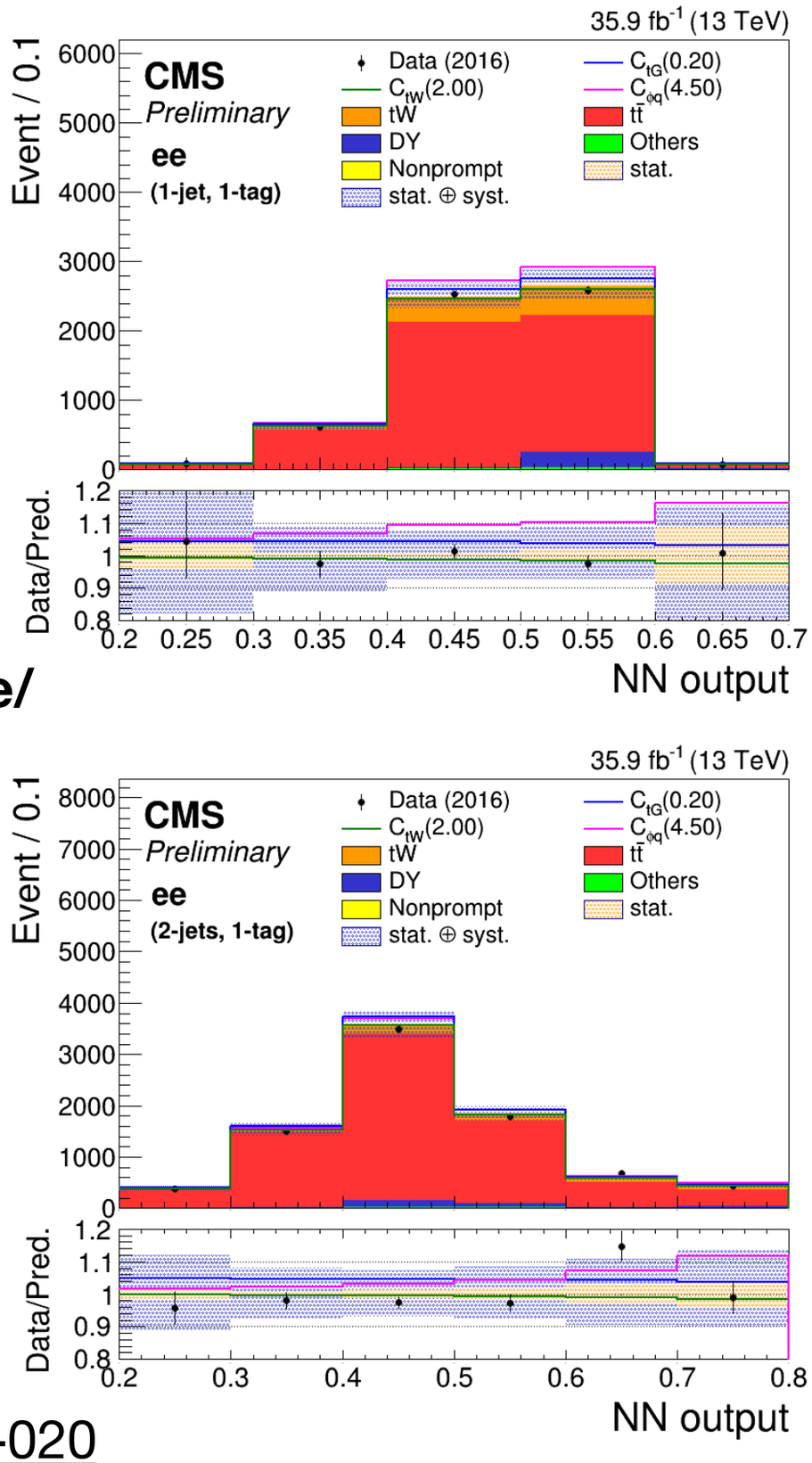
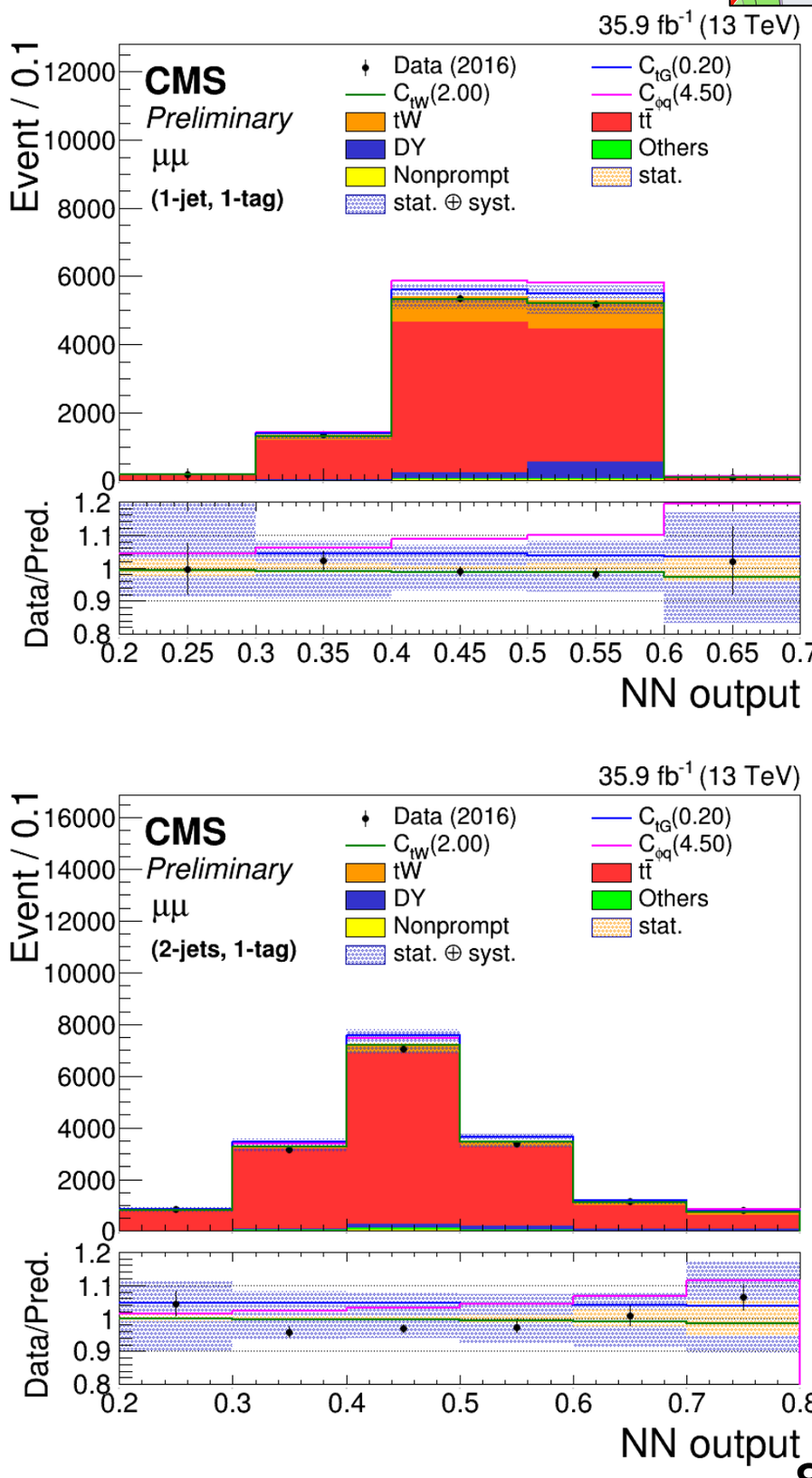
Neural net discriminants in ee/ μμ final states





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2016 Dataset
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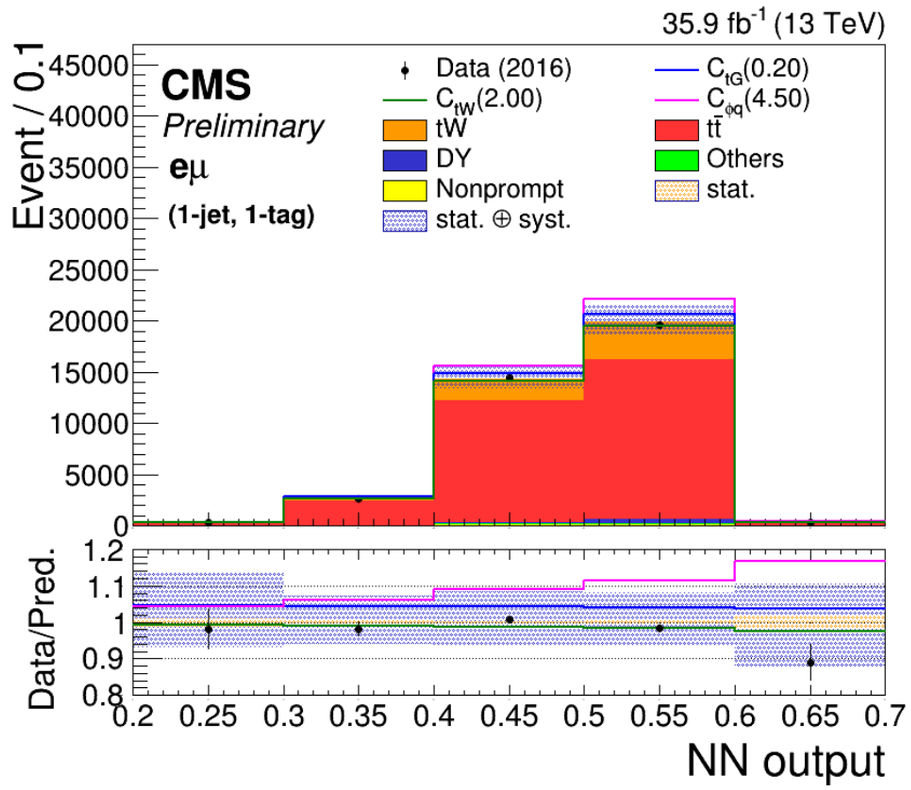
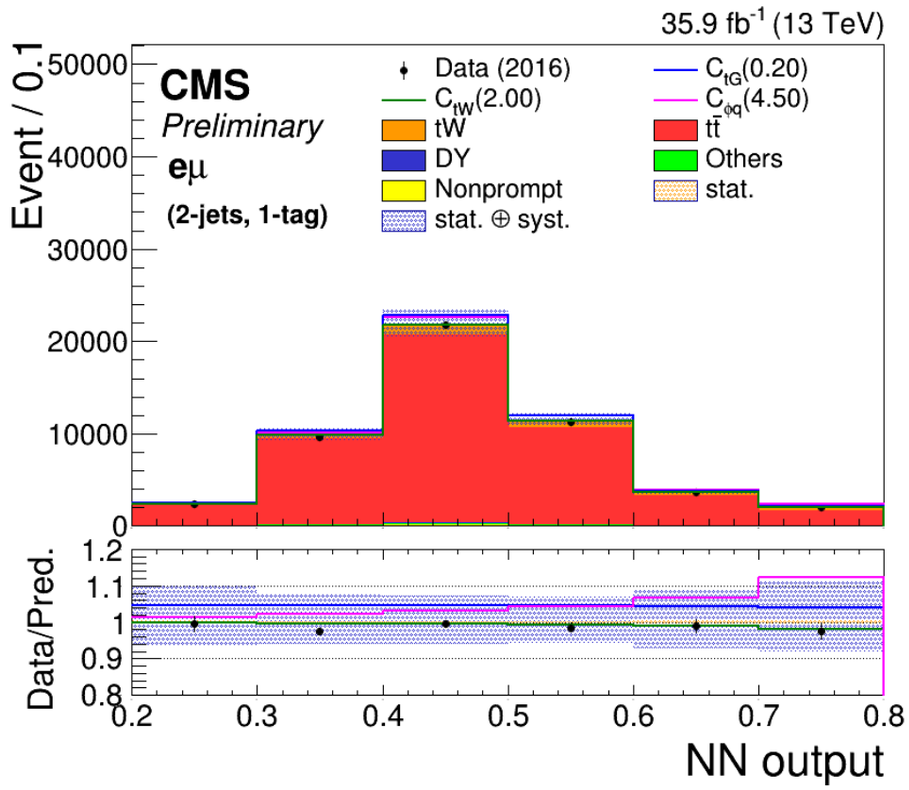
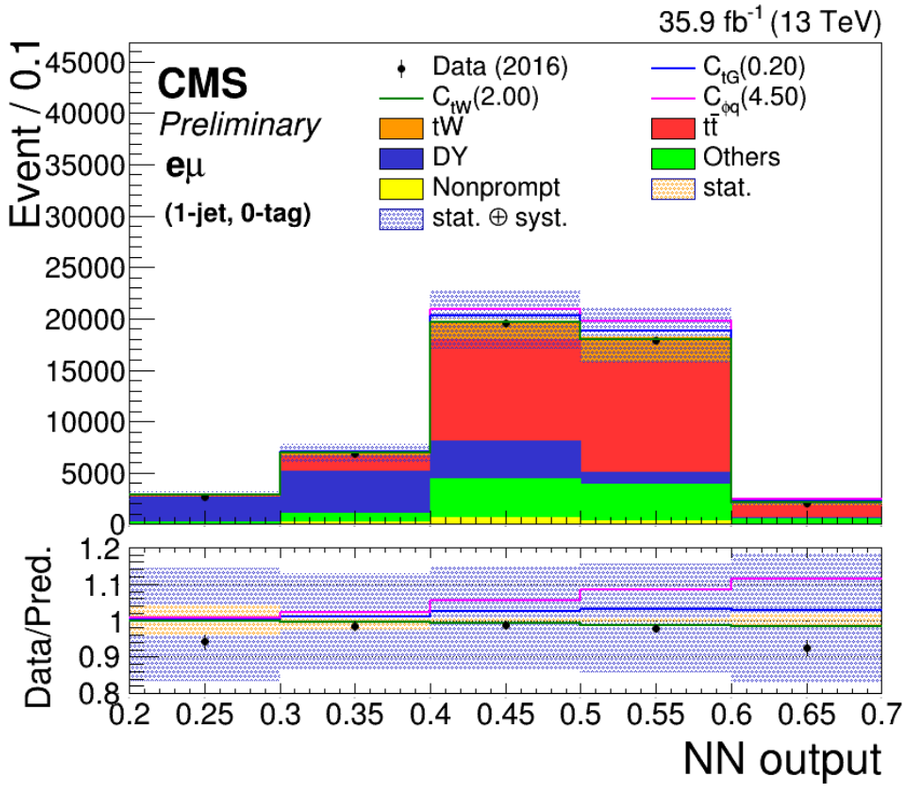
New Physics via top production





Neural net discriminants in eμ final states



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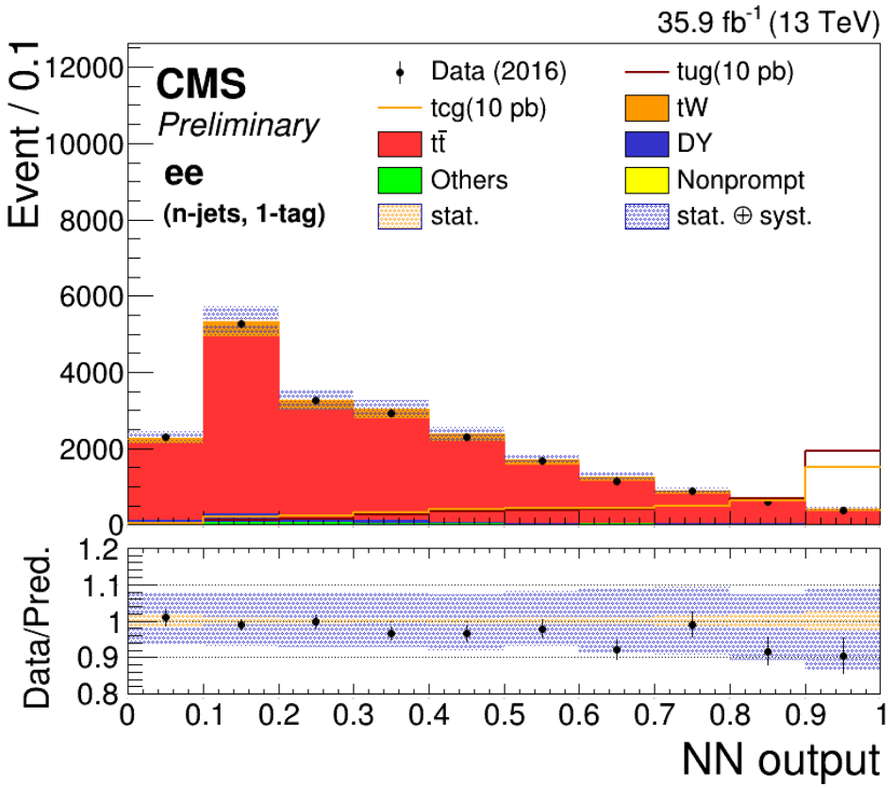
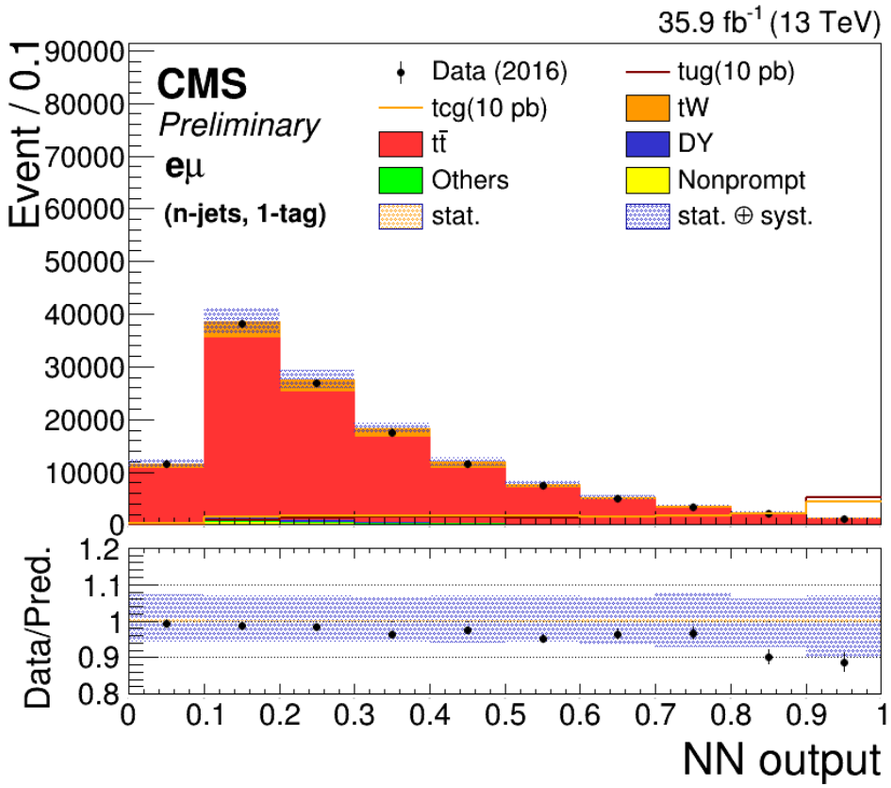
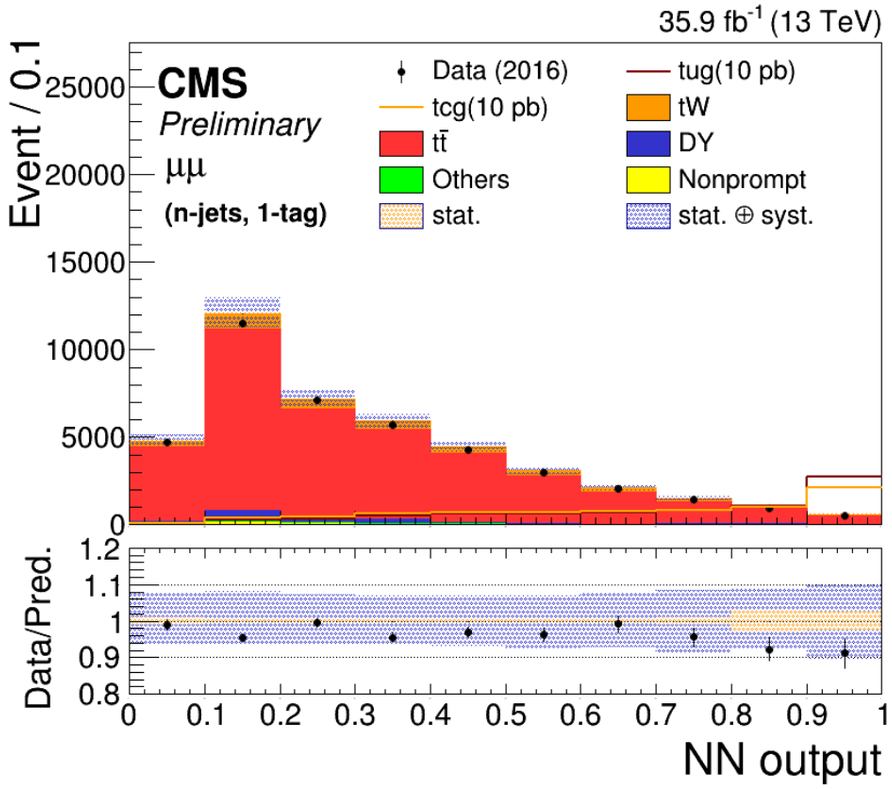




Neural net discriminants in 1-tag final states ee/μμ/eμ for FCNC operators



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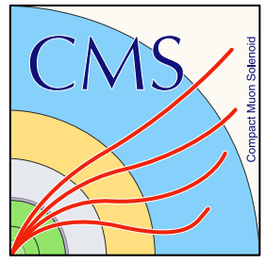
New Physics via top production



Eff. coupling	Channel	Observed	Expected
C_G	ee	$-0.14^{+0.51}_{-0.82}$ [−1.14 , 0.83]	$0.00^{+0.59}_{-0.90}$ [−1.20 , 0.88]
	eμ	$-0.18^{+0.42}_{-0.73}$ [−1.01 , 0.70]	$0.00^{+0.51}_{-0.82}$ [−1.08 , 0.77]
	$\mu\mu$	$-0.14^{+0.44}_{-0.75}$ [−1.06 , 0.75]	$0.00^{+0.57}_{-0.88}$ [−1.16 , 0.85]
	Combined	$-0.18^{+0.42}_{-0.73}$ [−1.01 , 0.70]	$0.00^{+0.51}_{-0.82}$ [−1.07 , 0.76]
$C^{(3)}_{\phi q}$	ee	$1.12^{+2.89}_{-1.18}$ [−4.03 , 4.37]	$0.00^{+1.74}_{-2.53}$ [−6.40 , 3.27]
	eμ	$-0.70^{+0.59}_{-2.16}$ [−3.74 , 1.61]	$0.00^{+1.12}_{-1.34}$ [−2.57 , 2.15]
	$\mu\mu$	$1.13^{+2.86}_{-0.87}$ [−3.58 , 4.46]	$0.00^{+1.92}_{-2.20}$ [−4.68 , 3.66]
	Combined	$-1.52^{-0.33}_{-2.71}$ [−3.82 , 0.63]	$0.00^{+0.88}_{-1.05}$ [−2.04 , 1.63]
C_{tW}	ee	$6.18^{+7.81}_{-3.02}$ [−4.16 , 8.95]	$0.00^{+6.81}_{-2.02}$ [−3.33 , 8.12]
	eμ	$1.64^{+5.59}_{-0.80}$ [−1.89 , 6.68]	$0.00^{+6.19}_{-1.40}$ [−2.39 , 7.18]
	$\mu\mu$	$-1.40^{+7.79}_{-3.00}$ [−4.23 , 9.01]	$0.00^{+6.97}_{-2.18}$ [−3.63 , 8.42]
	Combined	$2.38^{+4.57}_{+0.22}$ [−0.96 , 5.74]	$0.00^{+5.93}_{-1.14}$ [−1.91 , 6.70]
C_{tG}	ee	$-0.19^{+0.02}_{-0.40}$ [−0.65 , 0.22]	$0.00^{+0.21}_{-0.22}$ [−0.44 , 0.41]
	eμ	$-0.03^{+0.11}_{-0.19}$ [−0.34 , 0.27]	$0.00^{+0.15}_{-0.17}$ [−0.34 , 0.29]
	$\mu\mu$	$-0.15^{+0.02}_{-0.34}$ [−0.53 , 0.19]	$0.00^{+0.18}_{-0.19}$ [−0.40 , 0.35]
	Combined	$-0.13^{+0.02}_{-0.27}$ [−0.41 , 0.17]	$0.00^{+0.14}_{-0.15}$ [−0.30 , 0.28]
C_{uG}	ee	$-0.017^{+0.22}_{-0.22}$ [−0.37 ,0.37]	$0.00^{+0.29}_{-0.29}$ [−0.42 , 0.42]
	eμ	$-0.017^{+0.17}_{-0.17}$ [−0.29 ,0.29]	$0.00^{+0.26}_{-0.26}$ [−0.38 , 0.38]
	$\mu\mu$	$-0.017^{+0.17}_{-0.17}$ [−0.29 ,0.29]	$0.00^{+0.27}_{-0.27}$ [−0.38 , 0.38]
	Combined	$-0.017^{+0.13}_{-0.13}$ [−0.22 ,0.22]	$0.00^{+0.21}_{-0.21}$ [−0.30 , 0.30]
C_{cG}	ee	$-0.032^{+0.47}_{-0.47}$ [−0.78 ,0.78]	$0.00^{+0.63}_{-0.63}$ [−0.92 , 0.92]
	eμ	$-0.032^{+0.34}_{-0.34}$ [−0.60 ,0.60]	$0.00^{+0.56}_{-0.56}$ [−0.81 , 0.81]
	$\mu\mu$	$-0.032^{+0.36}_{-0.36}$ [−0.63 ,0.63]	$0.00^{+0.58}_{-0.58}$ [−0.84 , 0.84]
	Combined	$-0.032^{+0.26}_{-0.26}$ [−0.46 ,0.46]	$0.00^{+0.46}_{-0.46}$ [−0.65 , 0.65]

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